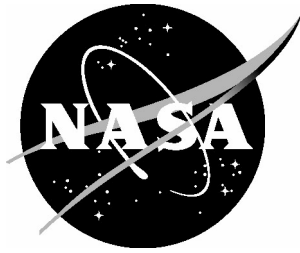


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# Flight Experiment Investigation of General Aviation Self-Separation and Sequencing Tasks

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May 2005

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## **Symbols & Abbreviations**

ADAHRS	Air Data, Attitude and Heading Reference System
ADS-B	Automatic Dependent Surveillance – Broadcast
AFFTC	Air Force Flight Test Center
AGL	Above Ground Level
AMM	Airport Management Module
ANOVA	Analysis of Variance
ATC	Air Traffic Control
ATIS	Automated Traffic Information System
ATOL	Air Traffic Operations Lab
CDAP	Conflict Detection, Alerting and Prevention
CDI	Course Deviation Indicator
CDTI	Cockpit Display of Traffic Information
Con Ops	Concept of Operations
DAS	Data Acquisition System
EMA	Exponential Moving Average
EP	Evaluation Pilot
ETA	Estimated Time of Arrival
ETE	Estimated Time Enroute
F	F-ratio
FAA	Federal Aviation Administration
FAF	Final Approach Fix
FPM	Feet Per Minute
FSIL	Flight Systems Integration Laboratory
ft.	feet
GA	General Aviation
GPS	Global Positioning System
HSI	Horizontal Situation Indicator
HVO	Higher Volume Operations
Hz	Hertz
IAF	Initial Approach Fix
IAP	Instrument Approach Procedure
IF	Intermediate Fix
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
KIAS	Knots Indicated Airspeed
kts	knots
LaRC	Langley Research Center
LCD	Liquid Crystal Display
LVDS	Low-Voltage Differential Serial
M	Mean (arithmetic average)
MAP	Missed Approach Point
MAS	Method of Approach Separation
MCH	Modified Cooper-Harper
MFD	Multi-Function Display
N	Sample size
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NCAM	National Consortium for Aviation Mobility

NLR	National Aerospace Laboratory
n. m.	nautical miles
p	Probability; level of (statistical) significance
PIC	Pilot In Command
PTS	Practical Test Standards
ReTA	Requested Time of Arrival
RMSE	Root Mean Squared Error
SATS	Small Aircraft Transportation System
SCA	Self Controlled Area
SD	Standard Deviation
SP	Safety Pilot
sps	samples per second
SSS	Self-Separation and Sequencing
TAA	Terminal Arrival Area
TMX	Traffic Manager software
$X^2$	Chi-square statistic

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## Introduction

The Small Aircraft Transportation System (SATS) Higher Volume Operations (HVO) Concept of Operations (Con Ops) proposes to dramatically increase operating capacity during Instrument Meteorological Conditions (IMC) at non-towered, non-radar equipped airports (i.e., “SATS candidate airports”) by enabling simultaneous operations of multiple aircraft [1]. Currently, National Airspace System (NAS) capacity is limited at these airports during poor weather because Air Traffic Control (ATC) procedural separation operations allow only one aircraft to fly either an approach or departure procedure at a time (i.e., single takeoff/departure or single approach/arrival) thus reducing airport capacity.

The National Aeronautics and Space Administration (NASA) developed SATS HVO procedures and Cockpit Display of Traffic Information (CDTI) formats for pilots to use for self-separation, thereby allowing multiple aircraft to operate simultaneously resulting in increased capacity at non-towered, non-radar equipped airports. A Self-Separation and Sequencing (SSS) Flight Experiment was conducted to determine the overall viability of these procedures and display formats. During this flight experiment, general aviation (GA) pilots hand-flew their aircraft while using a CDTI and the SATS HVO procedures to perform self-separation and sequencing tasks. Quantitative and qualitative data were collected to determine if there were any detrimental effects on pilots’ perceived workload levels and abilities to fly an instrument approach.

This report describes the test set up and results of the SSS Flight Experiment.

## Background

### *Problem Statement*

Although a capacity plateau has been reached within the United States for the commercial air transportation system and the NAS, demand for air transportation services continues to increase. An approach to increasing total air transportation system capacity and throughput is to enhance access to more than 5,000 smaller airports located within the United States. The majority of these smaller airports have no control towers and lie outside ATC radar coverage. However, such airports have the potential to provide convenient access and service to communities across the country [2].

### *SATS Solution*

NASA, partnered with the Federal Aviation Administration (FAA) and the National Consortium for Aviation Mobility (NCAM) (i.e., a consortium of U.S. industries, local and state governments, and research institutions including universities), is leading a research and development program focused on maturing technologies needed for SATS [3]. The long-term goal of SATS is to facilitate equitable, on-demand, widely distributed access to more communities in less time [3]. The near-term, five-year goal of the SATS Project is to “develop key airborne technologies [and procedures] that permit small aircraft operations during near all-weather conditions at and to virtually any touchdown zone at thousands of landing facilities (including small airports) in the United States” [2].

## ***SATS HVO***

The SATS Project's initial focus is to prove that four new operating capabilities will enable safe and affordable access to virtually any runway in the nation during most weather conditions. The four SATS Project objectives (or sub-elements) center on enabling operational capabilities that enhance operational efficiency in the current NAS environment. These objectives include:

- HVO at Non-Towered, Non-Radar Airports;
- Lower Landing Minimums at Minimally Equipped Landing Facilities;
- Increased Single-Pilot Crew Safety and Mission Reliability; and
- En Route Procedures and Systems for Integrated Fleet Operations.

The overall goal of the SATS HVO sub-element is to increase capacity by enabling the simultaneous operation of multiple aircraft in non-radar airspace at and around airports without air traffic control towers in nearly all-weather conditions. Two fundamental aspects of the SATS HVO Con Ops include a Self Controlled Area (SCA) and an Airport Management Module (AMM) [1]. The AMM is an automated ground module located at a SATS airport that will provide information regarding SCA status (i.e., active or inactive), as well as sequence number information to arriving aircraft so that pilots can sequence themselves onto the approach. The SCA is airspace that is established at a SATS airport (i.e., a non-towered, non-radar equipped airport) during IMC. Within the SCA, pilots are responsible for self-separation from other aircraft and for sequencing themselves onto the approach. Automatic Dependent Surveillance – Broadcast (ADS-B) is required by participating aircraft and along with a CDTI will enable self-separation. This self-separation capability and related procedures will allow the throughput associated with these types of airports to increase by reducing the need for ATC's procedural separation. Flight within the SCA will be governed by a set of rules and procedures rather than by the AMM.

Two primary conditions necessary for the success of the SATS HVO Con Ops are:

- Pilots must be able to sequence themselves for an instrument approach; and
- Pilots must be able self-separate before and during the approach.

## **Current Study**

The SSS Flight Experiment was conducted to collect quantitative and qualitative data to determine if GA pilots, asked to hand fly an aircraft while using a CDTI and related SATS HVO procedures, could perform self-separation and sequencing tasks without experiencing detrimental effects on their perceived workload levels and abilities to fly an instrument approach. The results of this experiment address the fundamental question regarding the overall viability of the SATS HVO Con Ops of simultaneous operations of multiple aircraft during IMC at non-towered, non-radar equipped airports [1].

## Research Objectives

The first objective of the SSS Flight Experiment was to determine if GA pilots can use a multi-function display (MFD) with traffic information, also referred to as a CDTI, to self-separate and sequence their ownship aircraft, while following an aircraft, into a non-towered, non-radar equipped airport during IMC. To answer this question, six GA pilots were asked to hand fly an aircraft according to the SATS HVO procedures defined for straight-in, in-trail approaches as well as “simultaneous arrival” approaches (i.e., approaches requiring aircraft to merge). The overall viability of the self-separation and sequencing tasks were evaluated in terms of percentage of time that separation and appropriate landing sequence were maintained.

The second objective of the SSS Flight Experiment was to assess how pilots’ workload and abilities to fly an aircraft are affected when they use a CDTI to self-separate and sequence their ownship aircraft into a non-towered, non-radar equipped airport during IMC. Subjective measures of workload and objective measures of flight path deviation were recorded while pilots performed the SATS HVO approach procedures. Pilots’ workload and flying proficiency levels were also measured when they performed straight-in, in-trail approaches and simultaneous arrival approaches using current day FAA GPS instrument approach procedures (i.e., without the use of SATS HVO procedures and a related CDTI), so that a baseline of each pilot’s flying proficiency could be established.

## Method

### Subjects

Six GA EPs participated as test subjects. All EPs were male, ranged in age between 19 – 46 years [Mean (M) = 24, Standard Deviation (SD) = 10], were instrument-rated and current to fly under Instrument Flight Rules (IFR), and held a high performance aircraft endorsement. Two of the EPs held private pilot certificates; four of the EPs held commercial pilot certificates; and four of the EPs held complex aircraft endorsements.

All EPs had less than 350 total flight hours (M = 276, SD = 52). On average, the EPs had flown approximately 29 hours during the last 90 days (M = 28.8, SD = 21.4), with four of the six EPs having flown at least 10 hours while using a global positioning system (GPS) device during the last 90 days. Four of the EPs had previous experience flying GPS instrument approaches, and five of the EPs had previous experience using a Horizontal Situation Indicator (HSI) flight instrument during flight.

Prior to participating in the SSS Flight Experiment, only one of the EPs had ever used a CDTI. None of the EPs were certified flight instructors, had previously flown a Cirrus SR22 aircraft, or had flown for the military. All EPs were treated in accordance with the “Ethical Principles of Psychologists and Code of Conduct” [4].

## Test Facilities and Apparatus

Facilities and apparatus for the SSS Flight Experiment included the test aircraft; airborne research software; and ground simulation software. These items are described in the following sections.

### *Test Aircraft*

The test aircraft used for this experiment was NASA Langley Research Center's (LaRC) Cirrus SR22X research aircraft. The SR22X (Figure 1) is a four-place, composite, fixed-gear aircraft with a single 310-horsepower piston engine. For this experiment, EPs flew the assigned experiment tasks from the left-side pilot's seat, while a NASA Safety Pilot (SP) flew at all other times from the right seat. An experimenter occupied the right aft seat and operated experiment equipment located in the aft area of the aircraft (Figure 2).



Figure 1. NASA LaRC's Cirrus SR22X research aircraft.

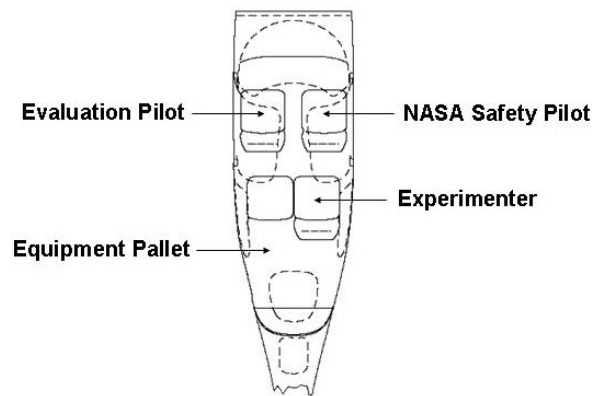


Figure 2. SR22X seating arrangement.

The Cirrus SR22X is one of several new-generation GA aircraft making use of the latest in materials, aerodynamics, avionics, and manufacturing technology [5]. NASA LaRC's Cirrus SR22X was modified by the addition of a GA baseline research system that included an additional power system to power the research systems; an ADAHRS; an Avidyne® MFD; an experimenter workstation; a Data Acquisition System (DAS); a sensor system and air data boom; two general-purpose computers; a video system; and an audio system [5]. Much of this equipment was mounted on the research equipment pallet located in the aircraft's aft compartment. For the SSS Flight Experiment, specific modifications to the GA baseline research system included the addition of experiment-specific software on the general-purpose computers, an additional audio channel for experimenter comments, and custom Jeppesen database cards for the Garmin 430 GPS. A detailed list of the data recorded by the DAS is included in Appendix A.

**Multi-Function Display.** The Avidyne® FlightMax® EX5000 MFD, located in the middle of the main instrument panel (Figure 3), was used to present the appropriate display information during each of the experiment's approach tasks. The MFD was a 10.4-inch diagonal liquid crystal display (LCD) with an 800 x 600 pixel resolution. The bezel panel around the display contained two rotary knobs and 10 bezel buttons for display and mode control. Outputs from the knobs and bezel buttons were transmitted to the general-purpose research computers on an RS-232 serial bus. The unit also accepted input display video from a low-voltage differential serial (LVDS) data bus from the research system to display research images on the MFD.



Figure 3. SR22X instrument panel.

**Horizontal Situation Indicator Display.** A Sandel 3800 HSI was configured throughout the experiment as shown in Figure 4. The HSI's navigation source was the number one Garmin 430 GPS.



Figure 4. HSI configuration.

### *Airborne Research Software*

The airborne research software served as a main component of the flight experiment in that it:

- Generated each approach scenario flown by the EP;
- Generated a simulated traffic aircraft for the EP to follow;
- Performed calculations and generated displays to enable the self-separation and self-sequencing

tasks;

- Generated the displays on the MFD;
- Detected potential conflicts between the SR22X and the simulated traffic aircraft;
- Generated visual and audio alerts associated with traffic conflicts;
- Generated visual information intended to assist the EP in the prevention of traffic conflicts;
- Logged scenario start time, scenario stop time, and information regarding loss of separation (lateral and vertical) between the SR22X and the simulated traffic aircraft;
- Corrected known erroneous Air Data, Attitude and Heading Reference System (ADAHRS) pitot static data (see Appendix B); and
- Flagged the MFD, if there was a loss of flight sensor data.

The majority of the airborne research software interface checks were performed on the ground using X-Plane® flight simulation software [6]. In-flight verification and validation of the airborne research software was completed during several pre-experiment, checkout flights.

**Traffic Generator.** The Netherlands' National Aerospace Laboratory's (NLR) traffic manager software (TMX) provided traffic generation and conflict detection, alerting, and prevention (CDAP) capabilities, and it also served as the main basis of the airborne research software utilized by the SSS Flight Experiment [7]. Additional software was developed for the interface between TMX and the MFD and ADAHRS [8, 9]. TMX was used to design and test flight scenarios, with both traffic and simulated ownship aircraft, before flight. The flight profile and performance of the traffic aircraft was specified for each flight scenario. The traffic aircraft's flight profile included its start position, heading, altitude, calibrated airspeed, and all subsequent waypoints, altitudes, and airspeeds. The same winds aloft conditions that the ownship aircraft encountered were used to compute the performance of the traffic aircraft. The beginning of each scenario started when the EP flew within a specified lateral and vertical distance of a predefined start waypoint. TMX provided consistent initial conditions between the traffic aircraft and ownship for each flight scenario among all EPs.

**Research Software.** Two critical enhancements were made to the TMX software (hereafter called research software) to enable SATS HVO operations for sequencing and self-separation. The first main enhancement to the research software was the addition of the capability to initialize both the ownship and traffic aircraft with a starting sequence number [10]. The sequence number identified the lead aircraft and the following aircraft. In all test conditions, the ownship aircraft was to follow the traffic aircraft on a GPS instrument approach into the destination airport. The other main enhancement to the research software enabled self-separation operations during the flight experiment [10]. This enhancement consisted of two principle components: a Requested Time of Arrival (ReTA) calculation, and a Proceed/Hold calculation. The ReTA was an internal calculation, not presented to the pilot, that determined the earliest clock time after which the ownship aircraft could depart the Intermediate Fix (IF) inbound on the approach and be reasonably assured of proper lateral separation from the traffic aircraft throughout the approach. The minimum lateral separation required throughout the approach was 3 nautical miles (n. m.).

The research software calculated ReTA based on the speed profiles of the traffic aircraft and the ownship aircraft. The traffic and ownship aircraft had two speeds that were planned to be flown during the approach [i.e., a constant airspeed up to the Final Approach Fix (FAF), followed by a speed reduction to final approach speed to the runway threshold]. Once the lead aircraft arrived within specified heading and distance values of the IF inbound, the research software, using the actual winds aloft derived onboard the ownship aircraft and the planned speed profile of the lead aircraft, calculated the lead aircraft's estimated time of arrival (ETA) at the runway threshold. Then, based on the planned speed profile of the ownship aircraft and derived winds aloft, the software calculated the estimated time enroute (ETE) of the ownship aircraft from the IF to the minimum lateral separation point plus a 0.5 n. m. margin (i.e., 3.5 n. m. from the runway threshold). This ETE was subtracted from the lead aircraft's ETA. Finally, 30 seconds were added to the last calculated time. This time period was used in addition to the 0.5 n.m. margin to create an additional buffer to account for minor pilot and aircraft performance uncertainties such as non-steady state performance and flight path parameter deviation allowances within the FAA's Instrument Rating Practical Test Standards (PTS) [11]. The resulting time was the ReTA for the ownship aircraft. For simplification, during all calculations, an instantaneous speed reduction by all aircraft was assumed at the speed reduction point. Thus, in equation form, the ReTA was calculated as follows:

- (1) Requested Time of Arrival (ReTA) = (ETA of simulated traffic aircraft at runway threshold) – (ETE of ownship aircraft from IF to 3.5 n. m. from runway threshold) + 30 seconds

If the ownship aircraft accelerated or decelerated inbound to the IF, a new ReTA was calculated using the new speed. In short, the ReTA, with some margin for error, was calculated to help ensure at least a minimum lateral separation of 3 n. m. at the planned closest point of approach (i.e., when the lead aircraft crossed the threshold). For a faster ownship aircraft, its ReTA would be later than a slower aircraft to ensure the same minimum separation when the lead aircraft crossed the threshold.

In an attempt to ease the workload associated with pilot mental calculations aloft, a simple tool was developed to assist the pilot in determining whether he had enough separation to begin the approach. This tool instructed the pilot, via the MFD, to either "Proceed" on the approach with proper separation or to "Hold" until proper separation could be guaranteed. Instead of displaying the ReTA to the EP, the research software calculated the ETA of the ownship aircraft at the IF. If the ETA was later than the ReTA, then the text "Proceed" was displayed to the EP, and the EP could fly over the IF waypoint inbound for the instrument approach. If the ETA was earlier than ReTA, then the text "Hold" was displayed to the EP, and the EP was required to hold until he received the "Proceed" indication from the software. It is important to note that the purpose of the Proceed/Hold tool was not to achieve a specific spacing between aircraft, but to help ensure that separation could be maintained throughout the approach.

### ***Ground Simulation Software***

The research software and the flight hardware, including the general-purpose computers and the Avidyne® MFD, were tested together in the NASA LaRC Flight Systems Integration Laboratory (FSIL) and, prior to flight, on-board the test airplane. X-Plane®, a commercially available flight simulation software, was used to provide parameters normally generated within the aircraft ADAHRS and GPS system during flight. These parameters included ground speed, track, heading, latitude, longitude, altitude, airspeed, vertical speed, and wind speed and direction.



## Evaluation Tasks

EPs evaluated three types of display formats while performing a series of straight in, in-trail and simultaneous arrival GPS instrument approach types. Each display type and approach type is described below.

### *Display Types*

The Avidyne® FlightMax® EX5000 MFD, located in the middle of the main instrument panel (Figure 3), was used to present the appropriate display information during each approach task.

**Baseline Display Format.** The display format in Figure 5 was used as a baseline to compare the effects of other additional information intended to aid the pilot with his self-separation task.

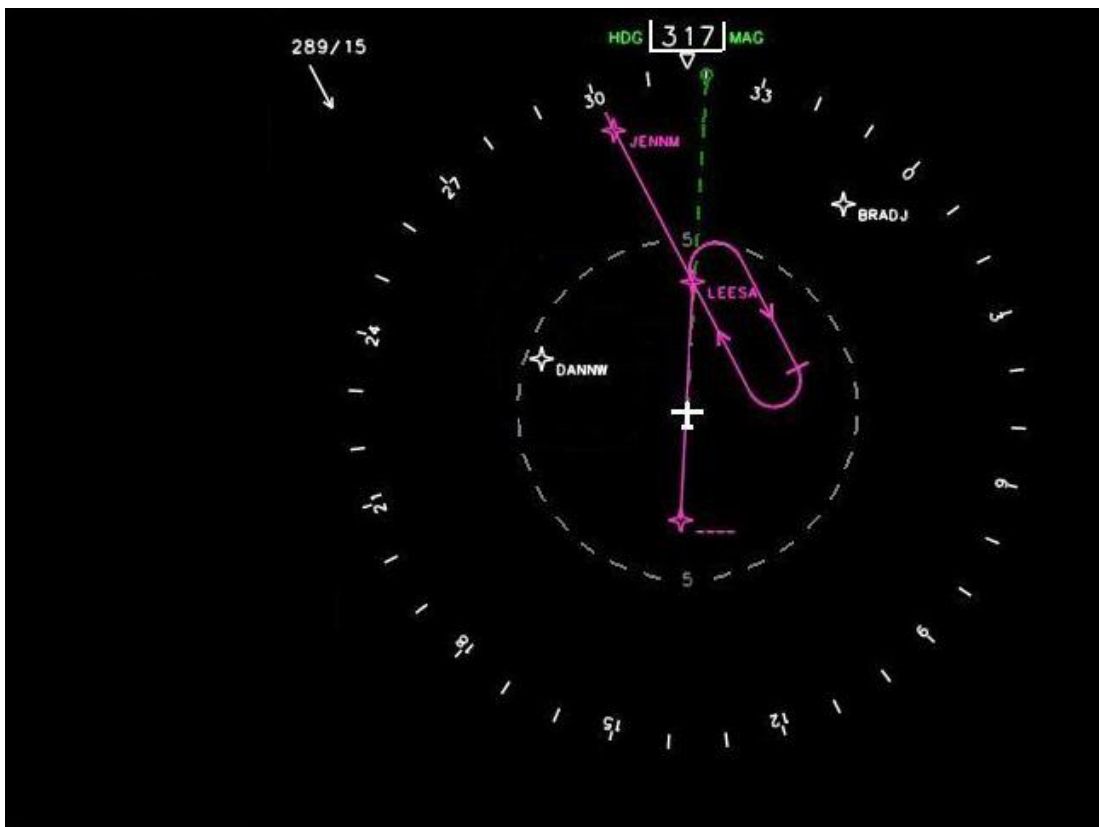


Figure 5. Baseline display format.

The baseline is a head-up format with a full-compass rose showing the magnetic heading of the ownship. An airplane symbol, representing ownship, is fixed in the center of the display. A map display, drawn with magenta lines between waypoints, shows the flight plan programmed in the GPS navigation system

relative to the airplane symbol. A green line drawn from the airplane symbol towards the top of the display represents the current ground track of the ownship. A range ring, with numerical value of distance from the ownship (numerical value is one-half of the map scale), is drawn around the airplane symbol. The magnetic heading and speed of the current winds computed in the research software are shown in the upper left-hand portion of the display.

A standard GPS holding pattern was displayed at the IF (when selected by the pilot during simultaneous approaches). The holding pattern turn radius was calculated by taking the planned indicated airspeed of the ownship aircraft [i.e., 120 knots indicated airspeed (KIAS)] plus the absolute value of the winds aloft. This accounted for the worst-case (widest) turn radius because of the assumed high ground speed for the ownship aircraft. The 4 n. m. outbound leg is also depicted on the display.

**MAS 1 Display Format.** The MAS 1 display format (Figure 6) has the same format as the baseline with the addition of other-traffic symbology and an approach and weather information box.

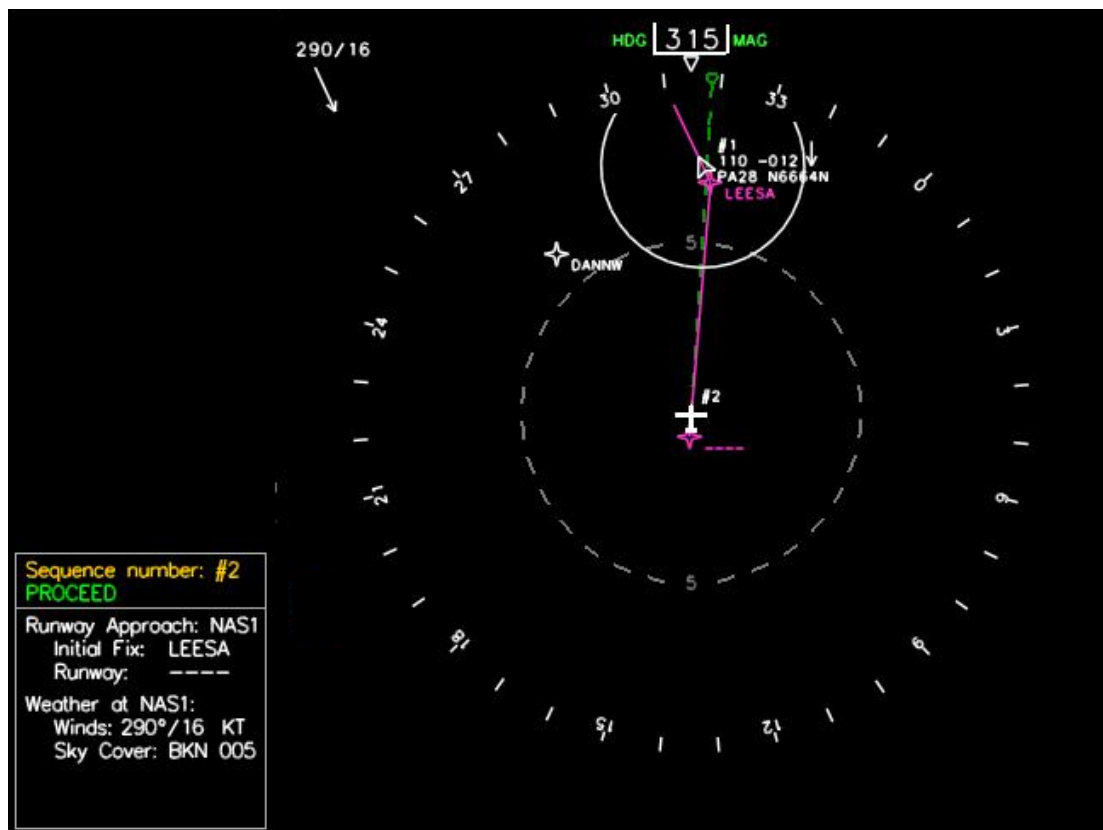


Figure 6. MAS 1 display format.

Other-traffic-aircraft are displayed as a chevron, relative to the ownship position and ground track, with a circle representing the minimum lateral separation to be maintained between ownship and the traffic aircraft. An aircraft information tag is attached to the chevron (Figure 7).



Figure 7. Traffic aircraft information.

The top line indicates the sequence of the particular traffic aircraft on the instrument approach for landing. In this example, “#1” indicates that the aircraft is the lead aircraft on the instrument approach to the airport. The second line indicates the computed calibrated airspeed, difference in altitude of the aircraft relative to ownship in hundreds of feet, and whether the traffic aircraft has a rate of climb or descent greater than 200 feet per minute (fpm). In this example, the traffic aircraft has a calibrated air speed of 110 kts based on calculations within the ownship aircraft from traffic state vector information and the winds aloft and atmospheric conditions measured from the ownship aircraft’s systems. The traffic aircraft is 1,200 ft. below the ownship aircraft and is descending. The third line indicates the type of traffic aircraft and its FAA aircraft registration number. In this example, the aircraft type is a PA28 with a registration number of N6664N.

An approach and weather information box is displayed on the lower left-hand side of the display. Figure 8 illustrates the information contained in the first two lines of that box.



Figure 8. Sequence number and “Proceed/Hold” text.

The first line in the top of the approach and weather information box shows the sequence number of ownship on the instrument approach to the airport. In this example, the ownship aircraft is the second aircraft currently on the approach. When another aircraft on the approach in front of the ownship aircraft completes the instrument approach, the sequence numbers cascade forward for all aircraft still conducting the approach (in this example, the ownship aircraft’s sequence number would change to #1). The ownship aircraft’s sequence number is also shown next to the ownship symbol in the middle of the display (Figure 9).

The CDTI concept used in the SSS Flight Experiment received traffic update information at the same one hertz (Hz) update rate that would have been experienced if the test aircraft’s avionics was receiving ADS-B information from an actual traffic aircraft. Since the EPs self-separated from simulated traffic during simulated IMC, an EP would not have been aware of any presentation differences between the display of a simulated traffic aircraft or an actual traffic aircraft.



Figure 9. Ownship aircraft and sequence number.

The second line of the approach and weather information box shows whether the ownship aircraft should proceed on with the approach or hold. The proceed indication (shown in green) and the hold indication (shown in amber) are computed based on whether proper time-based separation can be guaranteed. The remainder of the approach and weather information box shows the name of the instrument approach, the name of the initial fix on the instrument approach, the runway number on which to land, and the current winds and cloud heights above the airport as reported on the Automatic Terminal Information Service (ATIS).

**MAS 2 Display Format.** The MAS 2 display format (Figure 10) has the same format as the MAS 1 display with the addition of CDAP display information. The conflict prevention display information is drawn as conflict prevention bands on the airspeed and vertical speed indicators shown on the upper left-hand side of the display and on the compass rose. Conflict detection is also shown by color changes made to the conflicting traffic symbology (chevron, information tag, and minimum separation ring) and by audible tones on the intercom system.

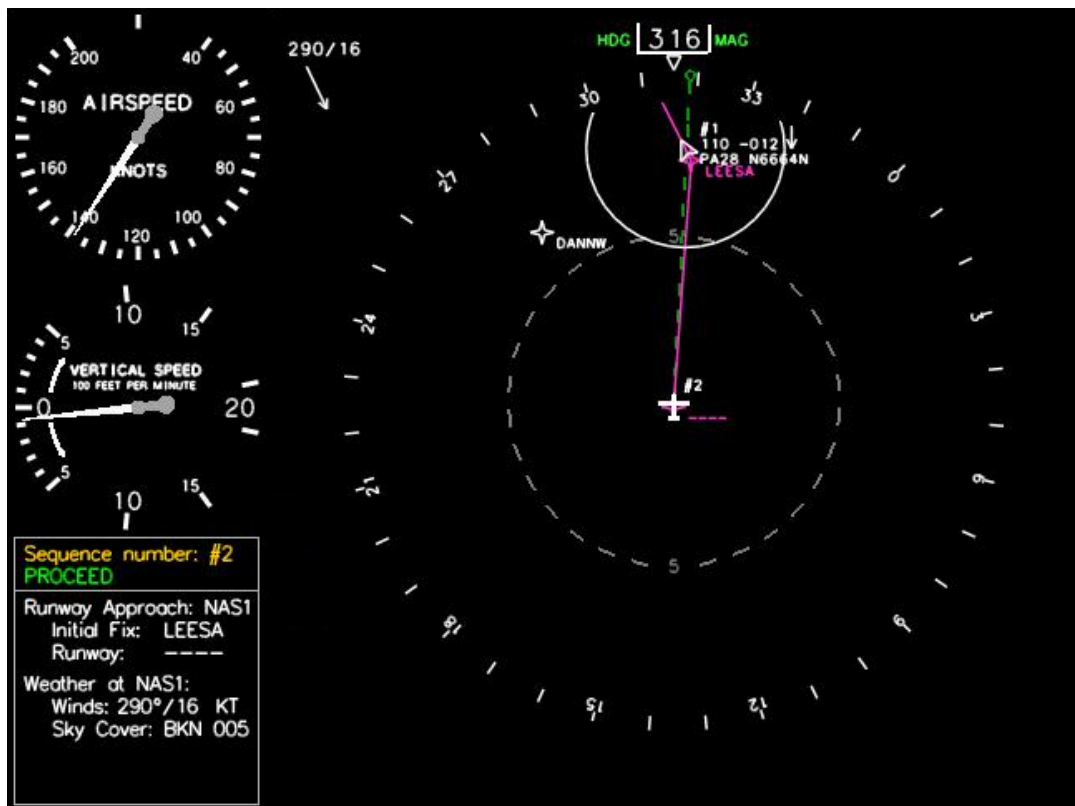


Figure 10. MAS 2 display format.

A conflict, or the potential loss of separation, occurs when the ownship aircraft's instantaneous flight path (state vector based) penetrates the lateral (3 n. m.) or vertical (+/- 1,000 ft.) airspace surrounding a traffic aircraft (during its state vector based flight path). Conflict detection is calculating within the next 30 seconds and the next 30 to 60 seconds, potential losses of separation between the ownship aircraft and all traffic aircraft. When a potential loss of separation is detected, the pilot of the ownship aircraft is notified with visual indications (i.e., a change in traffic aircraft display color) and audible alerts. Conflict prevention is calculating potential losses of separation with traffic aircraft based on a single parameter (e.g., airspeed, altitude, or heading). Conflict prevention bands indicate to the pilot, on the airspeed indicator, altimeter, or compass rose, which values to avoid to remain separated (i.e., the pilot should not fly into the indicated bands). When the prediction logic indicates a loss of separation within the next 30 to 60 seconds, an alert with cyan conflict prevention bands on either the airspeed or vertical speed indicator shows the pilot of the ownship aircraft the airspeed range or vertical speed range to avoid if loss of separation is to be prevented (Figures 11 and 12).



Figure 11. Vertical speed conflict prevention band.

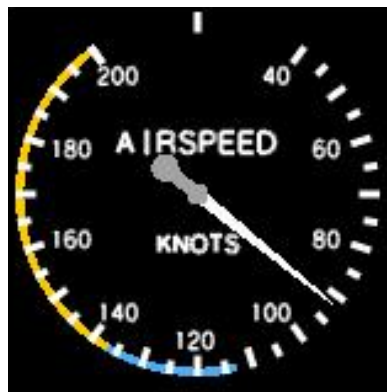


Figure 12. Airspeed conflict prevention bands.

If loss of separation is predicted to occur in less than 30 seconds, the conflict prevention bands are amber colored. If the ownship aircraft were to penetrate the minimum lateral separation from the other traffic, an audible tone would sound, and all conflict prevention bands, including a heading band, would appear on the display to assist the pilot with regaining separation.

## Approach Types

**Straight-In, In-Trail Approach.** Figure 13 depicts a typical scenario, including level-flight and step down procedures, used during the SSS Flight Experiment. During a straight-in, in-trail approach, the EP would proceed direct to the IF and fly the approach without any major changes in heading. The EP's task involved maintaining at least the minimum lateral separation while following the lead aircraft on the approach. As mentioned previously, the straight-in, in-trail scenarios were designed so that when the traffic aircraft landed, the ownship aircraft was 3.5 n. m. plus 30 seconds from the runway threshold.

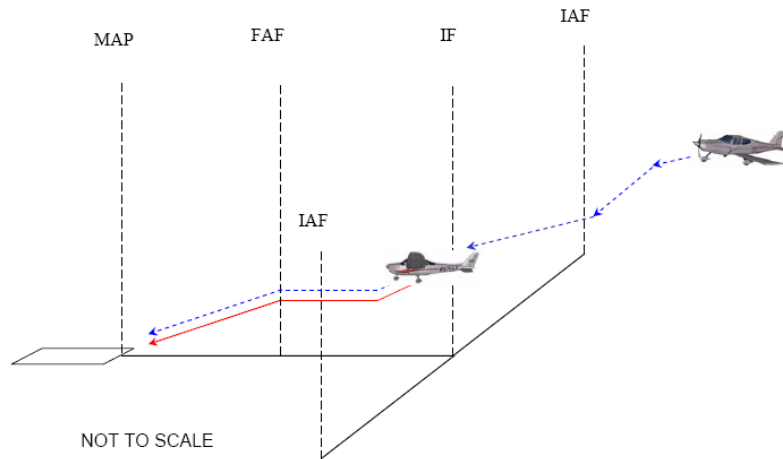


Figure 13. Straight in, in-trail approach diagram.

**Simultaneous Arrival Approach.** Figure 14 depicts a flight scenario that required EPs to fly a holding pattern before beginning the approach. During a simultaneous arrival, the flight scenarios were designed so that the ownship aircraft would arrive at the IF at nearly the same time as the lead aircraft. This forced the EP to maintain a vertical separation from the traffic aircraft and forced him to fly a holding pattern until receiving the “Proceed” message. EPs were required to complete the full hold so that SATS HVO simultaneous arrival approaches could be compared to the baseline simultaneous arrival approach. In actual implementation, a pilot could shorten the hold if given the “Proceed” indication early in the hold (as the EPs were given in the current experiment).

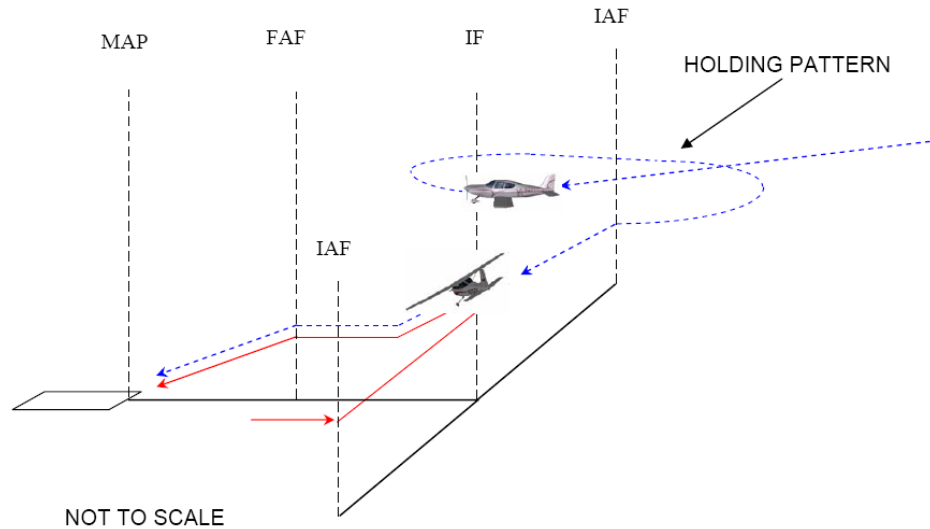


Figure 14. Simultaneous arrival approach diagram.

The self-separation task for both types of approaches ended when the ownship aircraft received the indication of having “Sequence #1” for the airport. This message was received after the lead aircraft had cleared the runway and was no longer a factor.

## Test Areas

To minimize the interference of non-participating aircraft with data runs, the data runs were performed at a minimum of 2,000 ft. above ground level (AGL), using virtual GPS instrument approaches, instead of into an airfield. To maximize flexibility with winds aloft, approaches to opposite ends of two perpendicular runways were developed (for a total of four different approaches). The flight experiment’s GPS instrument approaches were developed using the FAA’s standard terminal arrival area (TAA) criteria as an initial starting point (Figure 15) [12].

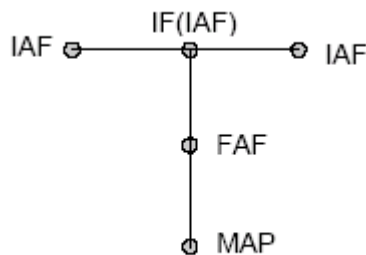


Figure 15. FAA’s standard GPS “T”.

Depending on the wind direction and presence of non-participating traffic on a particular flight day, one of the four different GPS instrument approaches was selected by the onboard experimenter.

Each GPS approach's waypoints were determined using Jeppesen's FliteMap IFR North America® software [13]. To support the self-separation task, a mandatory holding pattern, with the inbound course aligned with the final approach course, was established at the straight-in initial approach fix IF(IAF) for each runway. Flying direct to the IF allowed an arriving pilot to better anticipate the actions of other aircraft (this task would have been more difficult if all traffic aircraft had instead intercepted the final approach course at a different point). To minimize airspace used by the flight experiment, some of the opposing runway approaches were designed to utilize the same waypoint.

## **Approach Charts and Procedures**

An instrument approach procedures (IAP) chart was developed in-house for each of the four different approaches flown during this flight test. These charts, as shown in Figure 16, are similar in format to standard GPS IAP charts published by the FAA. The charts show the pilot the lateral path to be flown from one of four initial approach fixes (IAF) to the runway and then a path to a holding waypoint if a landing cannot be completed. The minimum altitude that a pilot can be at when passing the waypoints and the minimum descent altitude and minimum visibility necessary for the pilot to complete the landing are also shown.

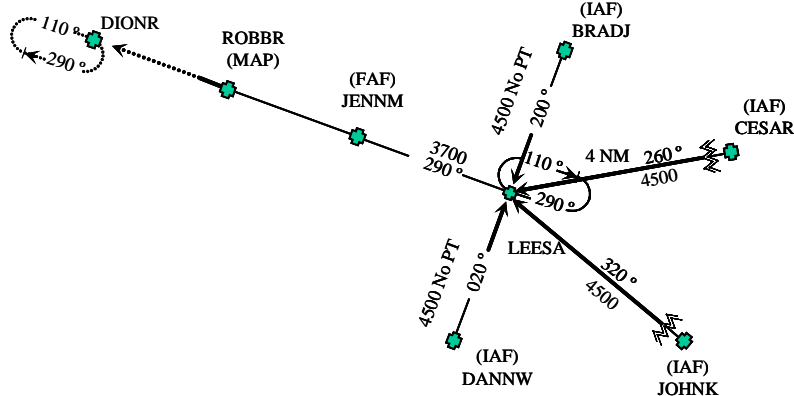
The SATS HVO instrument approach procedures utilized the same design criteria established by the FAA for normal GPS approaches except for modifications made to accommodate multiple aircraft simultaneously. These modifications included a holding pattern depicted at the IAF at the beginning of the final course in-bound to the runway 1,000 feet (ft.) above the minimum crossing altitude for that IAF. The SATS HVO procedures required aircraft that had no conflicting traffic between them and the runway to cross the IF at the minimum crossing altitude (4,500 ft. in Figure 16) and proceed with the approach without entering the holding pattern. If there was conflicting traffic, a "HOLD" message would be shown on the MFD, and the trailing aircraft would be required to hold 1,000 ft. above the preceding aircraft's IF minimum crossing altitude (5,500 ft. in Figure 16). When the preceding aircraft was no longer a conflict, a "PROCEED" message would be shown on the MFD, and the holding-aircraft could descend and start the approach. The "PROCEED/HOLD" messages were computed by the research software to assist the EPs in choosing the appropriate approach segment to fly (i.e., holding procedure or final approach course).



# GPS RWY 29

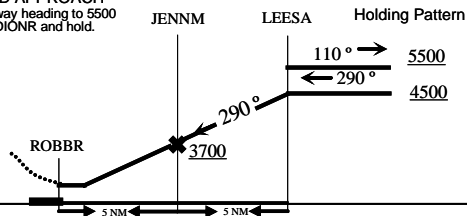
NASAVILLE FIELD (NASA)  
NASAVILLE, VIRGINIA

NORFOLK APP CON  
126.05 372.1  
UNICOM 123.0 (CTAF)

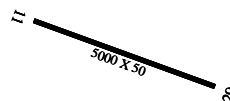


ELEV 2020

MISSED APPROACH  
Climb runway heading to 5500  
direct DIONR and hold.



CATEGORY	A	B	C	D
S-29	2420-1	400 (2000-1)		2020-1 1/4 400 (2000-1 1/4)



# GPS RWY 29

NASAVILLE FIELD (NASA)  
NASAVILLE, VIRGINIA

Figure 16. One of four typical SATS HVO approach charts.

For ease of implementation on the test aircraft, custom Approach Database cards containing SATS HVO approach database information were developed in conjunction with Jeppesen Sanderson, Inc. for use in the standard dual Garmin GNS 430 GPS/communication/navigation units installed onboard the SR22X. These cards enabled the EPs to fly the SATS HVO approaches using the SR22X's standard instrumentation with little additional training. When considering the airborne equipment, it is important to note that even though approaches were made to virtual airports, the responses of the avionics (as flown by EPs) were the same as if the approaches had been to actual airports.

**Procedures Used to Develop Experiment Flight Scenarios.** A unique flight scenario was developed for each of the four runways used during the SSS Flight Experiment. For each runway, a flight scenario was created to capture: 1) the courses of both IAFs to the IF, 2) approach type (i.e., straight-in, in-trail or simultaneous arrival with simulated traffic), 3) display type [i.e., Baseline, Method of Approach Separation (MAS) 1, or MAS 2], and 4) four wind variation considerations [i.e., 5, 15, 25, and 35 knots (kts)]. Initial conditions for position, heading, altitude, and airspeed for the traffic aircraft associated with each flight scenario were determined as well. As a result, a flight scenario database consisting of 192 flight configuration files (i.e., [(4 winds aloft conditions x 6 test conditions) x 2 inbound courses from the IAFs] x 4 runways]) was developed. This large number of scenario options allowed the onboard experimenter to account for true environmental conditions occurring during flight, thus producing the highest quality data for post-test processing.

The initial conditions for each of the flight scenarios (i.e., the start points for the ownship aircraft and the traffic aircraft) were defined such that when the lead (i.e., traffic) aircraft crossed the runway threshold, the ownship aircraft would always be located at the same distance in-trail behind the lead aircraft. Defining each flight scenario's initial conditions was accomplished using the Jeppesen FlightMap and the research software applications [10, 13].

A set of computer scenarios was developed for test in the NASA LaRC Air Traffic Operations Lab (ATOL), and then the same set of flight scenarios was designed to be loaded directly onto the test aircraft's experimental systems equipment. Each scenario was flown and tested in the ATOL to ensure its quality and correctness before being inserted into the SR22X data system. Additionally, pre-test flights were performed to verify software configurations and display functionality.

## **Experiment Design**

The experiment design used for data collection was a 2 [Approach Type (Straight In, In-trail and Simultaneous Arrival)] x 3 [Display Type (Baseline, Method of Approach Separation 1, and Method of Approach Separation 2)] full-factorial, within-subject design (Figure 17). Six EPs performed all six test conditions twice in partially counterbalanced order under simulated IMC using Foggles. Test conditions were presented in partially counterbalanced order (i.e., each test condition preceded and followed every other test condition and was presented an equal number of times) to control for ordering effects. Since each test condition was completed twice, the term "replicate #1" is used to describe the first time that a test condition was performed, and the term "replicate #2" is used to describe the second time that a test condition was performed.

<b>DISPLAY TYPE</b>	Baseline	Evaluation Pilots 1 - 6	Evaluation Pilots 1 - 6
	Method of Approach Separation (MAS) 1	Evaluation Pilots 1 - 6	Evaluation Pilots 1 - 6
	Method of Approach Separation (MAS) 2	Evaluation Pilots 1 - 6	Evaluation Pilots 1 - 6
		Straight In, In-trail	Simultaneous Arrival
<b>APPROACH TYPE</b>			

Figure 17. Experiment design matrix.

Detailed information regarding the method used to develop flight scenarios associated with combinations of display type and approach type as well as combinations of runways and winds aloft is provided above in the “Approach Charts and Procedures” section. Although 72 data runs were performed during this experiment, only 48 of those runs used the SATS HVO display formats and procedures and had traffic for the EP to follow. The other 24 runs involved procedural separation and use of the baseline display format. Data runs involving the use of the baseline display format and current day approach procedures were used to compare pilot tracking performance and workload with the runs using the SATS HVO display formats and procedures.

### ***Independent Variables***

The two independent variables used in the experiment design were display type and approach type.

### ***Dependent Measures***

**Separation Breaches and Landing Sequence Blunders.** For each scenario involving SATS HVO procedures, EPs were instructed to maintain at least 3 n. m. of lateral separation or 1,000 ft. of vertical separation between their ownship aircraft and traffic aircraft and were instructed to maintain landing sequence #2 at all times.

The employment of separation standards for the SATS HVO SSS Flight Experiment was based on those standards that ATC has established for aircraft operating on IFR flight plans, below 18,000 ft. within a radar environment. When aircraft were at the same altitude, a minimum of 3 n. m. separation was required. Three nautical miles were required for either longitudinal (in-trail) or lateral separation. Since both values were the same for this experiment, in this document the term “lateral separation” refers

to both longitudinal and lateral separation. When aircraft are within 3 n. m. laterally of each other, a 1,000 ft. minimum vertical separation is required. During the SSS Flight Experiment, EPs were deemed to have been vertically separated (within 3 n. m. of traffic) if they remained separated from the traffic aircraft by at least 825 ft. This altitude difference occurred as a result of the  $\pm 100$  ft. allowance in the FAA's Instrument Rating PTS and an allowable  $\pm 75$  ft. error in the ownship aircraft altimeter [11]. There was no altitude allowance for the traffic aircraft (which was simulated) since it "flew" without error.

Frequency counts and durations (i.e., elapsed times) of separation breaches and landing sequence blunders were collected to enable the calculation of the percentage of time that separation and appropriate landing sequence were maintained.

**Flight Path Parameter Deviation.** The EPs were instructed to maintain assigned altitude within 100 ft. and maintain assigned airspeed within 10 kts while conducting each instrument approach. These minima are specified in the FAA's Instrument Rating PTS [11]. The EPs were also instructed to maintain a lateral path deviation less than a full-scale deflection on the HSI course deviation indicator (CDI) ( $\pm 1.0$  n. m.) while on each approach prior to the IF waypoint and within three-quarter scale deflection ( $\pm 0.225$  n. m.) when past the IF waypoint.

**Subjective Assessments of Workload.** Subjective assessments of workload for each test run were obtained through the use of the Air Force Flight Test Center's (AFFTC) Seven-Point Subjective Workload Estimate Scale and the Modified Cooper-Harper (MCH) Rating Scale [14, 15]. The AFFTC's subjective workload estimate scale required EPs to integrate contributing factors to workload (activity level, system demands, time loads, and safety concerns) and arrive at an overall workload rating ranging from "1" (indicating nothing to do; no system demands) to "7" (indicating overloaded; system unmanageable; essential tasks undone; unsafe) (Figure 18).

- 1) Nothing to do; No system demands.
- 2) Light activity; Minimum demands.
- 3) Moderate activity; Easily managed; Considerable spare time.
- 4) Busy; Challenging but manageable; Adequate time available.
- 5) Very busy; Demanding to manage; Barely enough time.
- 6) Extremely busy; Very difficult; Non-essential tasks postponed.
- 7) Overloaded; System unmanageable; Essential tasks undone; Unsafe.

Figure 18. Air Force Flight Test Center's (AFFTC) Seven-Point Subjective Workload Estimate Scale.

The MCH Rating Scale required EPs to make a series of decisions regarding: whether or not the instructed task could be accomplished most of the time; if adequate performance was attainable (i.e., if errors were small and inconsequential); and whether or not the level of mental workload required by the

instructed task was acceptable. Upon answering questions according to a predetermined logical sequence, an overall rating ranging from “1” (indicating that the instructed task was very easy/highly desirable; operator mental effort was minimal; and desired performance was easily attainable) to “10” (indicating that the instructed task was impossible; it could not be accomplished reliably) was selected (Figure 19).

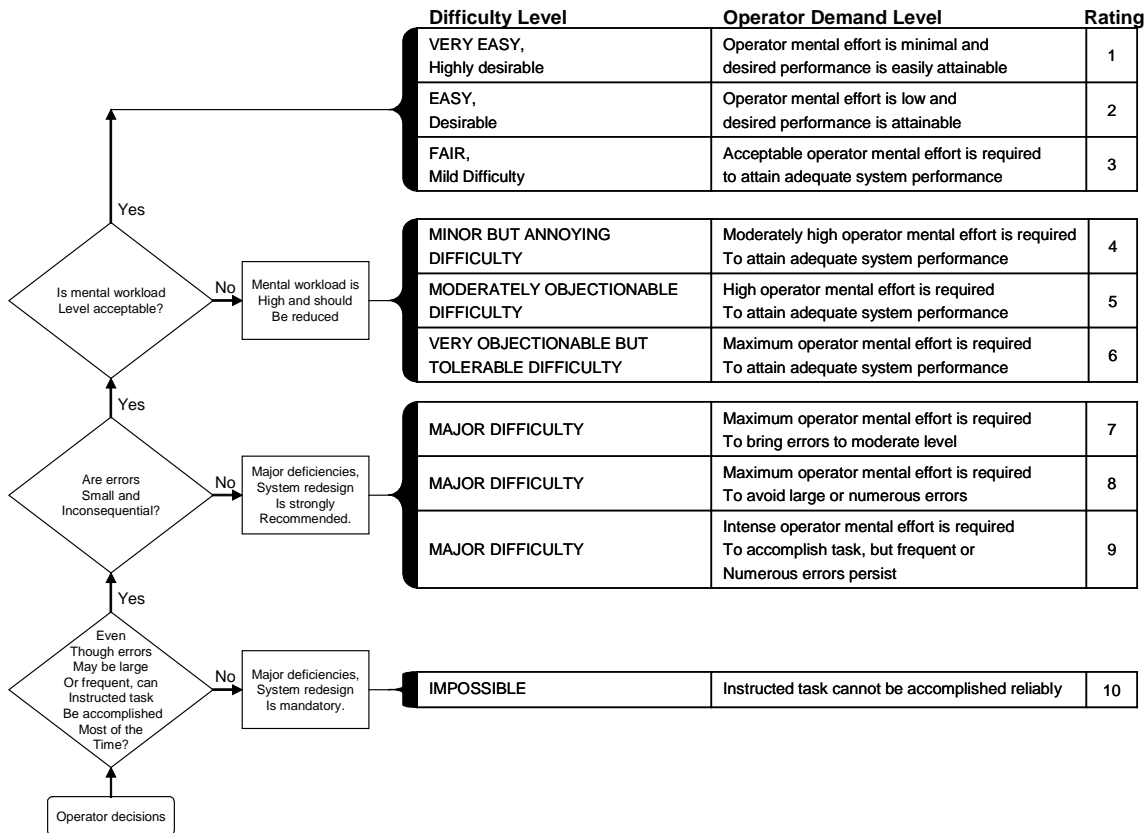


Figure 19. Modified Cooper-Harper (MCH) Rating Scale.

## Procedure

Each EP individually completed a pre-experiment session, a “classroom” training session, an “in-the-aircraft” training session, a familiarization flight, four experiment flights (during which the EP completed each of the six test conditions twice), and a post-experiment debriefing session. Each EP participated in the experiment over the course of three approximately eight and a half hour days.

A 15-minute pre-experiment session involved obtaining EPs’ total and recent flight hour data and asking EPs to read and sign an informed consent form. During the 3 hour “classroom” training session which immediately followed the pre-experiment session, an experimenter presented the EPs with slides that provided an overview of: 1) the HVO sub-element of the SATS Project, 2) the purpose of the SSS

Flight Experiment, 3) the experiment design matrix, 4) NASA LaRC's SR22X research aircraft, 4) the experiment equipment and procedures, 5) the test areas, 6) the GPS instrument approach tasks, including use of the Garmin 430, 7) the interpretation of the HSI, 8) the MFD and its operation, and 9) the subjective workload estimate scales. The “classroom” training session also involved having the EPs complete simulated approaches (both baseline and SATS HVO) using a simulated Cirrus aircraft, a simulated Garmin 430 GPS, and a simulated MFD with traffic information and software produced bezel buttons [9]. Components of this desktop simulation flight are shown in Figure 20.



Figure 20. Components of the “classroom” training session’s desktop simulation flight.

An “in-the-aircraft” training session, lasting approximately 30 minutes, immediately followed the classroom training session. This session provided review and reinforcement of material covered in the classroom session and was conducted in the SR22X. The EPs were given a “hands-on” tour and review of the SR22X cockpit instruments, avionics, intercom, flight controls, and MFD and were encouraged to ask questions about any unclear items or procedures.

After the “in-the-aircraft” training session, the EP, an experimenter, and a NASA SP conducted a familiarization flight. This flight lasted approximately 2 hours and was used to familiarize the EP with the flight characteristics and power settings of the SR22X as well as all aspects of the tasks he would be asked to perform during subsequent experiment flights. After takeoff, departure, climb, and level-off by the NASA SP, control of the aircraft was transferred to the EP. The EP was then guided through a series of basic flight maneuvers, including straight-and-level flight, standard-rate turns, and 700 fpm descents. Following these basic flight maneuvers, the EP was guided through two test conditions involving straight-in, in-trail approaches and two test conditions involving simultaneous arrival approaches. The NASA SP flew the aircraft during the transitions between test conditions. The four “practice test conditions” and the procedures under which they were conducted were designed to progressively expose an EP to all of the component tasks and procedures that would be asked of him during the test runs. Throughout the familiarization flight, the EP’s performance was assessed and remedial instruction and commentary was provided, as necessary, to assure his full understanding of the expected experiment flight procedures. At the conclusion of the familiarization flight, the NASA SP resumed control of the aircraft and landed. This concluded the first day of the experiment.

During the second and third days of the experiment, four data collection flights were completed. As on the familiarization flight, the NASA SP performed the takeoff, climb, and level-off, and then control was transferred to the EP. Unlike on the familiarization flight, the EP no longer received explicit procedures training for the required tasks and was directed to perform test conditions by the onboard experimenter. During each test condition, EPs were instructed to make position reports at the IF, FAF, and missed approach point (MAP). When the approaches associated with a given data collection flight were completed, the NASA SP again resumed control of the aircraft and landed. A 30-minute debriefing session after the final data collection flight completed the experiment's schedule.

The experimenter and the NASA SP carried out specific duties during both the familiarization and experiment flights. The experimenter selected the appropriate flight scenario and ensured that the appropriate information appeared on the CDTI; solicited and recorded the EP's test condition workload ratings; operated the experiment pallet and video recording system; and provided simulated ATC instructions to the EP as part of the prescribed experiment flight tasks. The experimenter also directed the NASA SP in repositioning the aircraft for each upcoming flight task. The NASA SP performed takeoffs, departures, arrivals, and landings; repositioned the aircraft between the EP's flight tasks; coordinated and communicated with ATC; and acted as pilot-in-command (PIC) throughout each flight.

### ***SP Checklist***

A GPS/HSI checklist was developed for use by the NASA SP so that the Garmin 430 GPS and the Sandel 3800 HSI would be consistently configured for every EP. This ensured proper sequencing and selection of the correct start waypoints on the Garmin 430 during the approaches and ensured that the proper navigation page was displayed to the EPs.

### ***EP Checklist***

EPs were provided with a checklist for use during the approach procedures to provide consistency among the EPs in their performance of the GPS approaches. This checklist specified manifold pressure settings, airspeeds, aircraft configuration, communication points, and Garmin 430 interaction at specific points during the approach. Power settings at experiment-specific airspeeds and configurations, for straight-and-level flight and descents, were determined during sensor checkout flights.

## **Results and Discussion**

A flight experiment was conducted to assess whether GA pilots could use a CDTI and related SATS HVO procedures to self-separate and sequence their ownship aircraft behind a traffic aircraft at a non-towered, non-radar airport during IMC. The effects of two different initial conditions between ownship aircraft and traffic as well as the effects of two different CDTI formats compared to a baseline display format with no other traffic displayed were investigated. Statistical analyses were performed to examine: 1) separation breaches and landing sequence blunders, 2) flight path parameter deviations, 3) adherence to FAA PTS performance criteria for the Instrument Rating, and 4) subjective assessments of workload.

A 5-percent significance level for the statistical analyses of all data collected in this experiment was set a priori. Detailed results of the statistical analyses may be found in Appendixes D, E, and F.

## **Separation Breaches and Landing Sequence Blunders**

Examining the 48 test runs that had a traffic aircraft included and where the SATS HVO procedures were used in conjunction with a CDTI showed that: 1) there were no lateral or in-trail losses of separation ( $\leq 3$  n.m.); 2) there were no vertical losses of separation ( $\leq 1,000$  ft.); and 3) there were no losses of proper landing sequence. The EPs successfully self-separated and sequenced themselves 100-percent of the time from a single traffic aircraft. This finding demonstrates that GA pilots could use a CDTI and related SATS HVO procedures to self-separate from and sequence their ownship aircraft with one other traffic aircraft into a non-towered, non-radar equipped airport during IMC under the given conditions of this experiment.

Data from the 24 test runs involving the use of the baseline display format and current day instrument approach procedures were not included in this analysis since other traffic was not displayed to the EPs during those runs.

## **Flight Path Parameter Deviation**

Deviations from assigned altitude and airspeed and the lateral path deviations from the assigned route on the instrument approach were used to quantify flight performance for each of the runs with two different initial conditions and three different MFD formats. Root mean squared error (RMSE) values were calculated for these parameters for each test run. Airspeed and lateral path deviation data were assessed during both level-flight and descents. Altitude data were assessed only during level-flight segments. Details of these calculations may be found in Appendix C.

A series of 2 (Approach Type) x 3 (Display Type) x 2 (Replicate) Analysis of Variance (ANOVA) tests was conducted on the RMSE values of altitude, airspeed, and lateral path deviations to determine if significant differences existed in these values when a given display type was used during a given approach type [16, 17, 18]. Detailed results of the flight path parameter deviation data analyses are available in Appendix D.

### ***Altitude and Lateral Path Deviation***

Analyses of the RMSE values associated with altitude and lateral path deviation revealed that:

- No statistically significant differences ( $p > 0.05$ ) were found to exist among the altitude and lateral path deviation data associated with approach type;
- No statistically significant differences ( $p > 0.05$ ) were found to exist among the altitude and lateral path deviation data associated with display type; and



- No significant ( $p > 0.05$ ) Approach Type x Display Type interaction effects were found to exist.

These results indicate that EPs were able to maintain the appropriate altitude and lateral path equally well when they performed straight-in, in-trail approaches and simultaneous arrival approaches; when they performed approaches using the Baseline display format, the MAS 1 display format, and MAS 2 display format; and when they performed different approach types using different display types. Altitude RMSE values associated with all six test conditions (Figure 21) reveal means of approximately 40 ft. and standard deviations of approximately 13 ft., and lateral path RMSE values associated with all six test conditions (Figure 22) reveal means of approximately 0.08 n. m. and standard deviations of approximately 0.04 n. m.

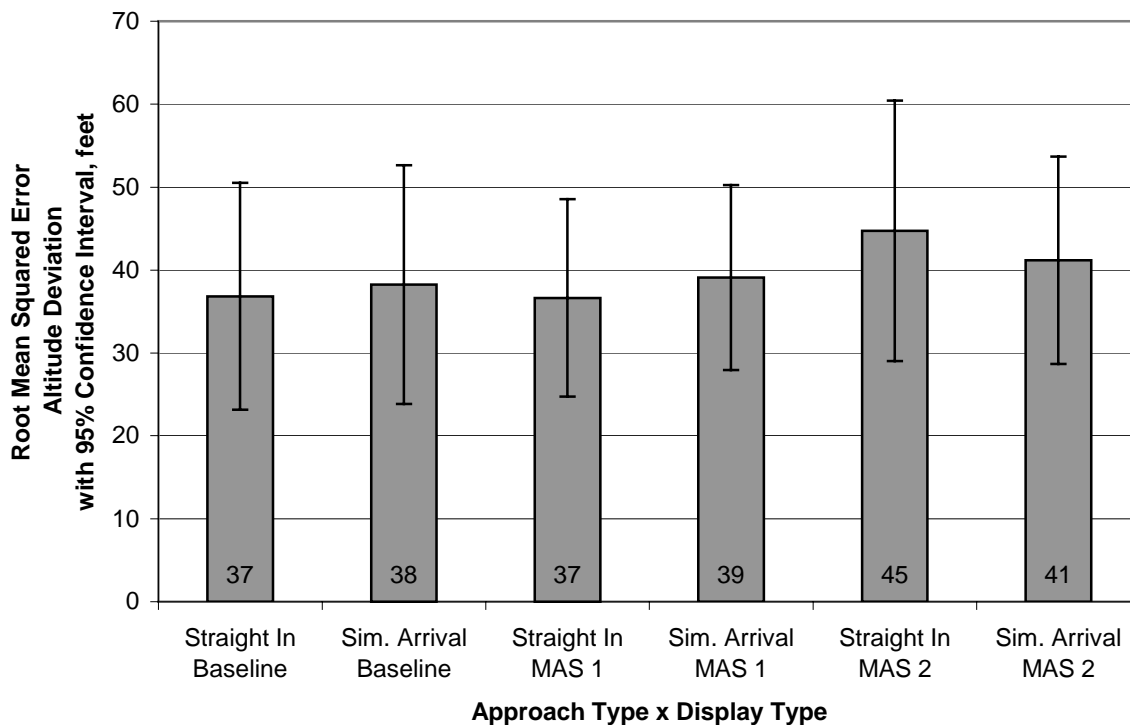


Figure 21. Mean altitude deviations associated with Approach Type x Display Type.

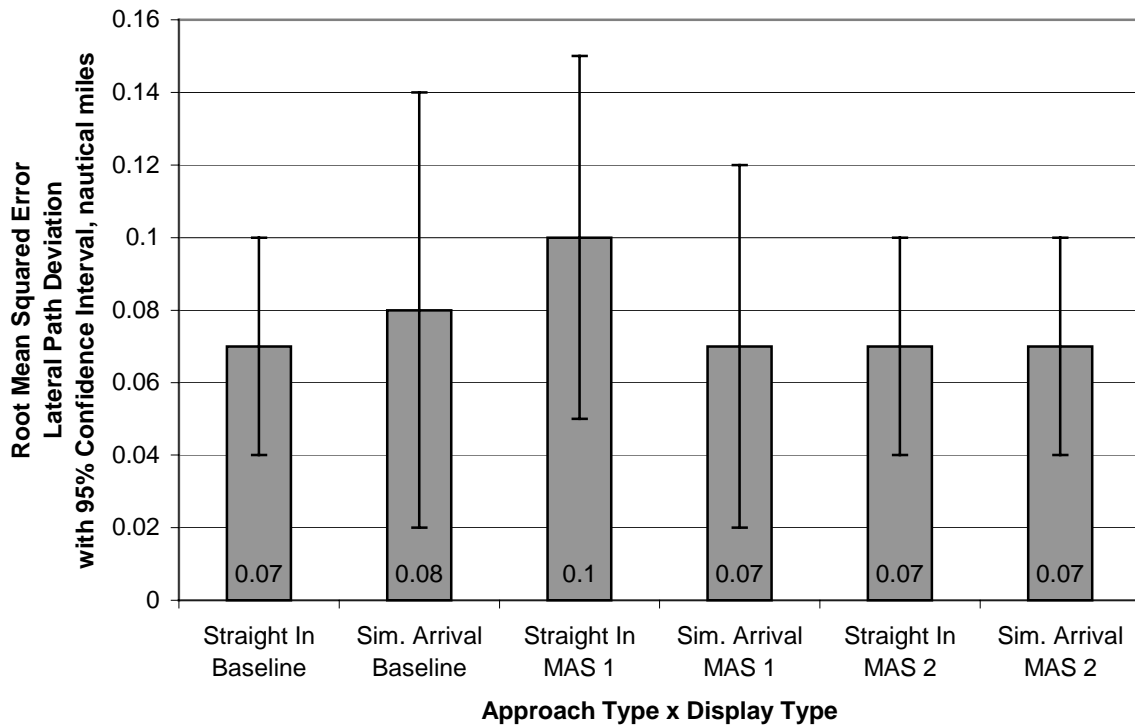


Figure 22. Mean lateral path deviations associated with Approach Type x Display Type.

An analysis of the altitude RMSE values associated with each replicate revealed that smaller altitude deviations occurred when EPs completed replicate #2 ( $F [1, 5] = 7.44$ ;  $p = 0.041$ ). This finding is most likely a result of a practice or learning effect since EPs always performed replicate #2 after completing replicate #1.

### *Airspeed*

EPs were able to maintain the appropriate airspeed equally well when they performed approaches using the Baseline display format, the MAS 1 display format, and MAS 2 display format and when they performed different approach types using different display types. Airspeed RMSE values associated with all six test conditions (Figure 23) reveal means of approximately 3 knots and standard deviations of approximately 1 knot.

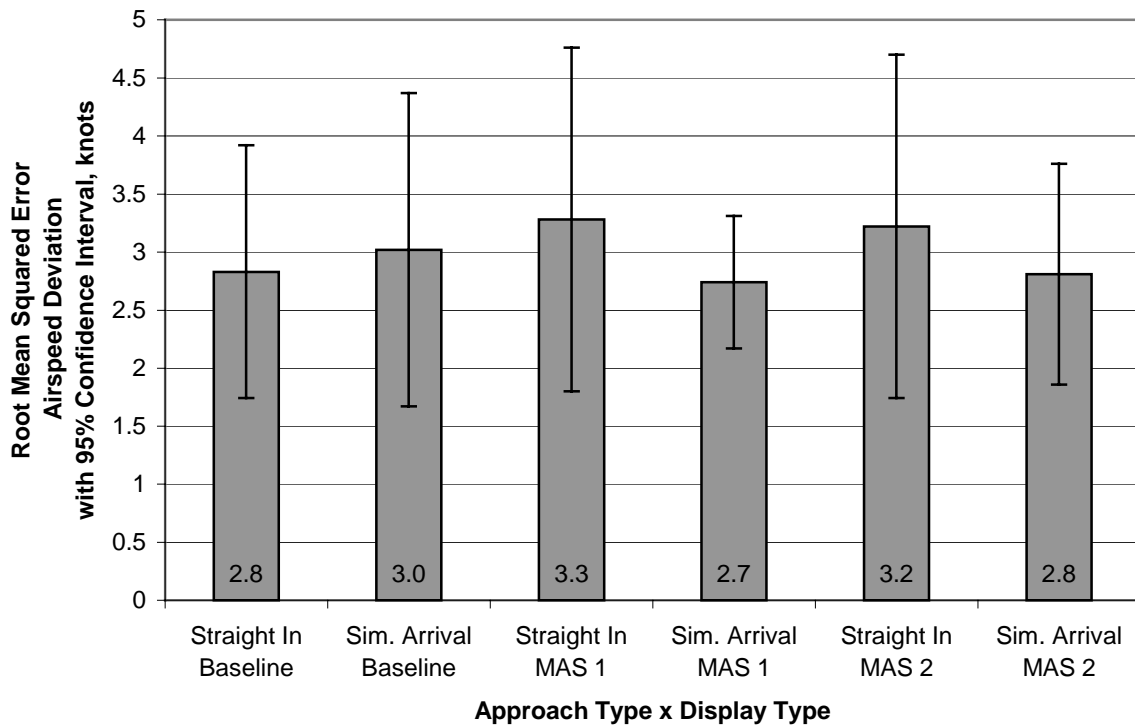


Figure 23. Mean airspeed deviations associated with Approach Type x Display Type.

At a statistically significant level, EPs were able to maintain airspeeds more accurately when they performed simultaneous arrival approaches than when they performed straight-in, in-trail approaches ( $F[1, 5] = 6.80$ ;  $p = 0.048$ ). Although this finding is statistically significant, a mean airspeed difference of just one-quarter of a knot (i.e., 0.25 kt) is operationally insignificant since, even under the best conditions, a pilot would be challenged to maintain airspeed within plus or minus 1.0 kt using an aircraft's standard instruments.

Overall, the analyses of the RMSE values associated with the SSS Flight Experiment's test conditions indicated that flight path parameter deviations did not increase when the SATS HVO self-separation and sequencing tasks were added to a baseline GPS instrument approach. EPs flew the SR22X research aircraft equally well when they performed baseline GPS instrument approaches and when they performed SATS HVO approaches.

### Adherence to PTS for the Instrument Rating

Percentages of time that EPs failed to adhere to the PTS for the Instrument Rating were also used to quantify flight performance. The duration (i.e., elapsed time in seconds) of each failure to fly within the PTS was the difference between the point in time when a PTS parameter was breached and the point in time when adherence to that PTS parameter was regained. For a given flight path parameter, the total time associated with failures to fly within PTS performance criteria was divided by the total time flying to obtain a percentage of time spent flying out of PTS conformance.

Percentages of time that EPs failed to adhere to the PTS were calculated for altitude, airspeed, and lateral path deviation. Data used to assess PTS conformance were obtained from 30-second segments during descents where the parameters would be stabilized. Airspeed and lateral path deviation data were assessed during both level-flight and descents. Altitude data were assessed only during level-flight segments.

All EPs successfully adhered to the PTS performance criteria for lateral tracking for the Instrument Rating (i.e.,  $\pm 1.0$  n. m. prior to the FAF, and  $\pm 0.225$  n. m. after the FAF) 100-percent of the time. Therefore, 2 (Approach Type) x 3 (Display Type) x 2 (Replicate) ANOVAs were only conducted on the percentages of time that EPs failed to adhere to the PTS for altitude and airspeed to determine if significant differences existed in these values when a given display type was used during a given approach type [16, 17, 18]. Analyses of the altitude and airspeed data in terms of adherence to PTS revealed that, for each flight path parameter, EPs adhered to the corresponding PTS equally well when they performed straight-in, in-trail approaches and simultaneous arrival approaches; when they performed approaches using the Baseline display format, the MAS 1 display format, and MAS 2 display format; and when they performed different approach types using different display types. These findings indicate that the EPs' abilities to fly the SR22X research aircraft during GPS instrument approaches were not affected by the addition of self-separation and sequencing tasks. Detailed results of these data analyses are available in Appendix E.

Percentages of altitude PTS nonconformance associated with all six test conditions (Figure 24) reveal means of approximately 1.5-percent and standard deviations of approximately 2.8-percent, and percentages of airspeed PTS nonconformance associated with all six test conditions (Figure 25) reveal means of approximately 0.7-percent and standard deviations of approximately 1.8-percent. (Note that a value of zero indicates conformance 100-percent of the time.)

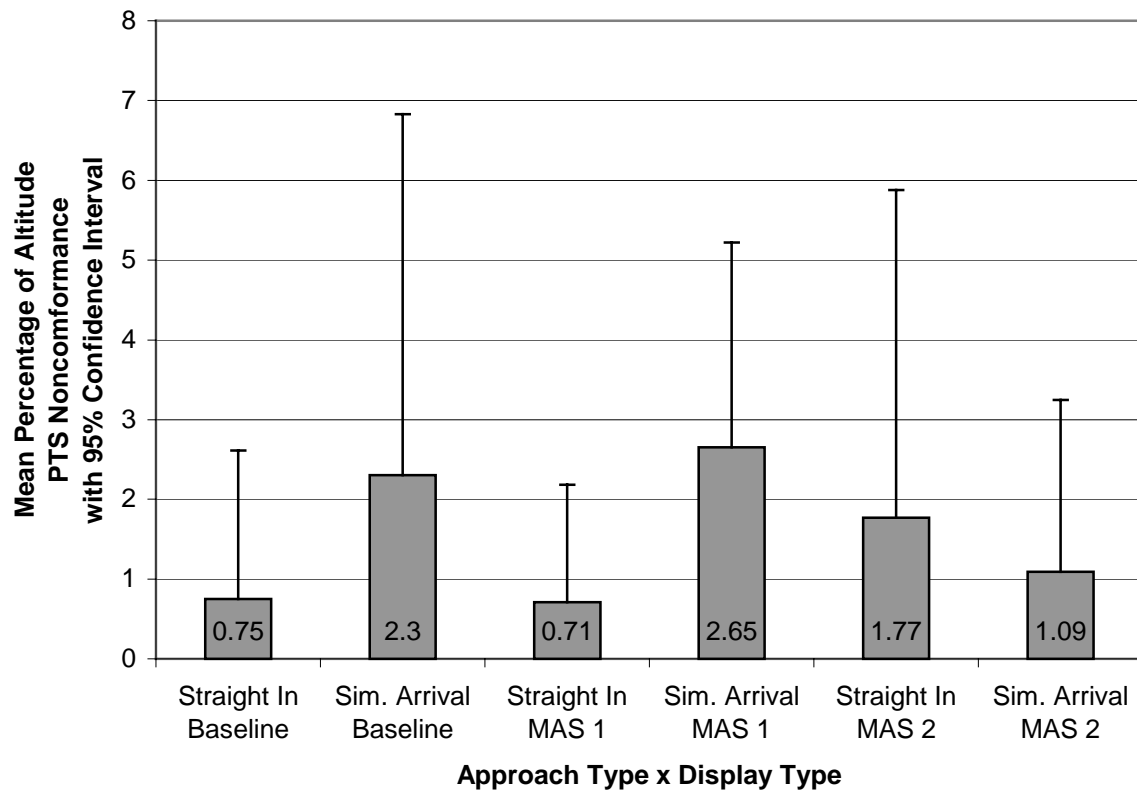


Figure 24. Mean percentages of altitude Practical Test Standard (PTS) nonconformance associated with Approach Type x Display Type.

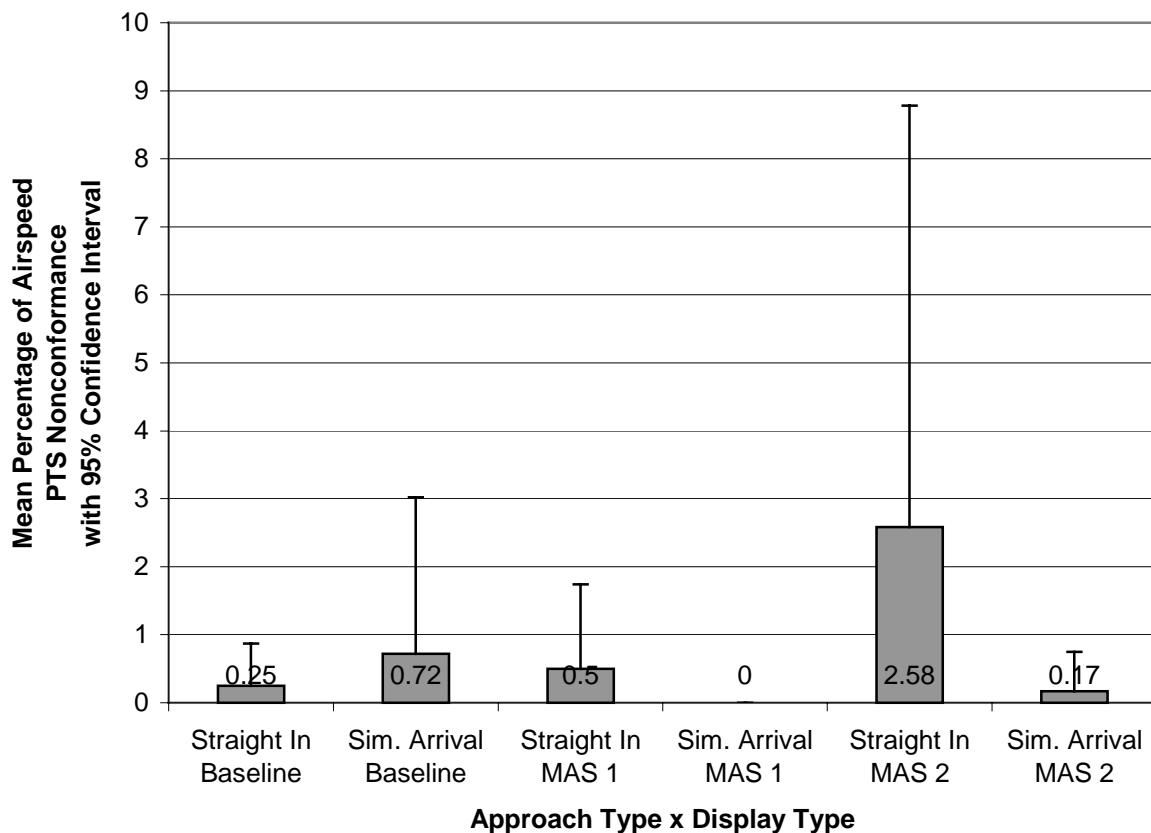


Figure 25. Mean percentages of airspeed Practical Test Standards (PTS) nonconformance associated with Approach Type x Display Type.

## Subjective Assessments of Workload

The AFFTC's Seven-Point Subjective Workload Estimate Scale and the MCH Rating Scale were used by the EPs to rate the level of workload that they experienced during each of the experiment's six unique test conditions [14, 15]. Each of the EPs flew each of the six test conditions twice. An average rating for each test condition for each EP was computed. This procedure was used for both rating scales with the results used for workload analyses. Nonparametric tests were employed as a conservative method for analyzing workload ratings associated with discrete rating scale items. Detailed results of these analyses are available in Appendix F.

The analyses of the AFFTC Subjective Workload Estimate Rating Scale data and the MCH Workload Rating data revealed that EPs reported experiencing equivalent levels of workload when they performed straight-in, in-trail approaches and simultaneous arrival approaches; when they performed approaches using the Baseline display format, the MAS 1 display format, and MAS 2 display format; and when they performed different approach types using different display types. These results suggest that the EPs' perceptions of workload were not affected by the additional tasks of self-separating and sequencing

during GPS instrument approaches.

AFFTC workload ratings associated with all six test conditions (Figure 26) reveal means of approximately 2.7 and standard deviations of approximately 0.5, and MCH workload ratings associated with all six test conditions (Figure 27) reveal means of approximately 2.3 and standard deviations of approximately 1.0.

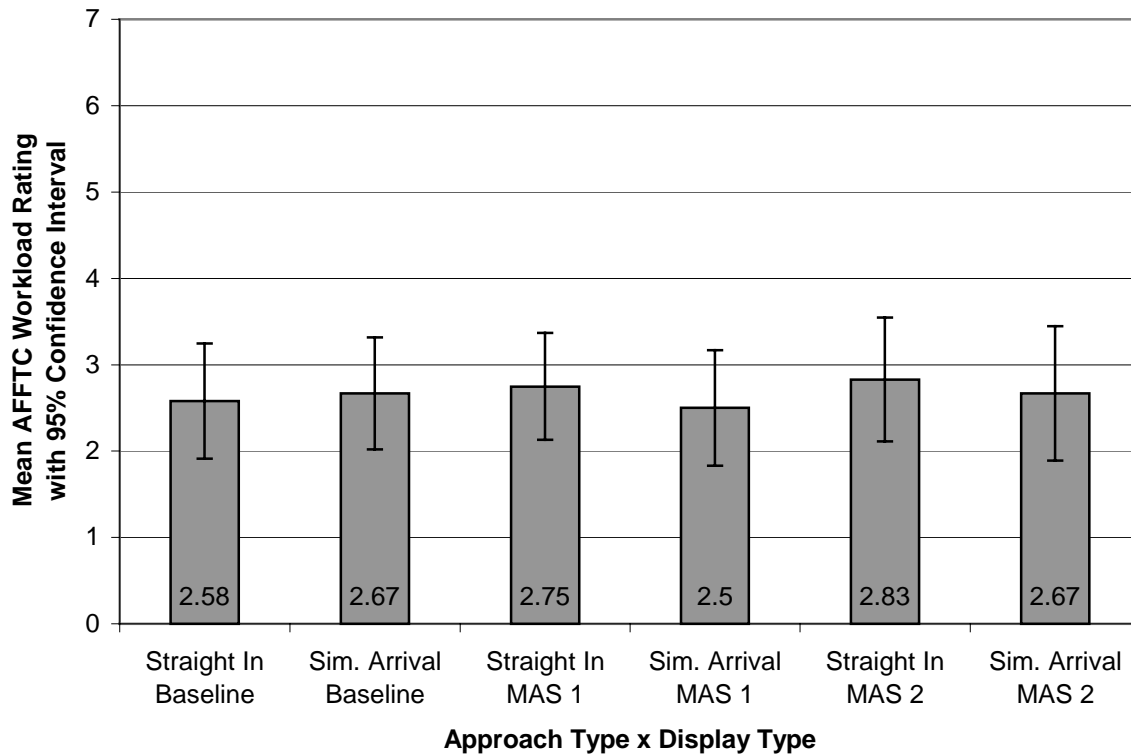


Figure 26. Mean Air Force Flight Test Center (AFFTC) Subjective Workload Estimate Scale ratings associated with Approach Type x Display Type.

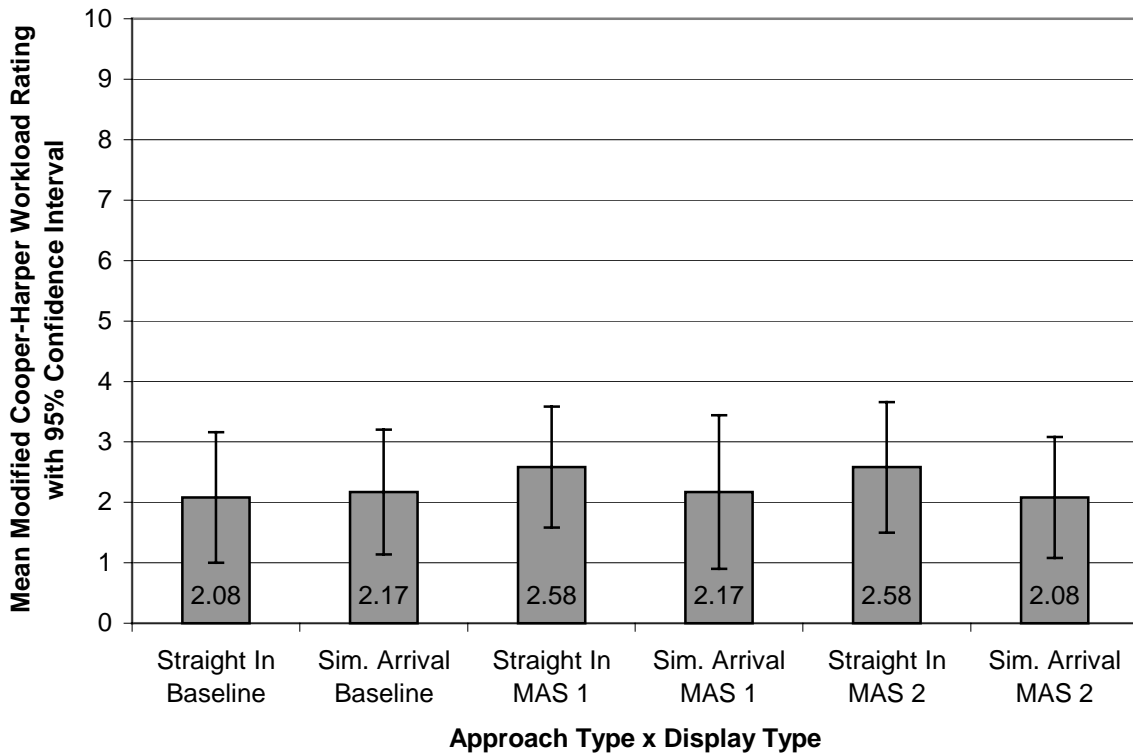


Figure 27. Mean Modified Cooper-Harper (MCH) workload ratings associated with Approach Type x Display Type.

## Conclusions

Two critical pilot tasks integral to the SATS HVO Con Ops include self-separation and sequencing. The focus of the SSS Flight Experiment was to determine the feasibility of asking GA pilots to self-separate and sequence their ownship aircraft for and during an instrument approach at a non-towered, non-radar equipped airport during IMC. The experiment concentrated on assessing the impact of the self-separation and sequencing tasks on EPs' performance of GPS instrument approaches and perceptions of workload during IMC. The additional information displayed to EPs participating in this experiment included CDTI, Proceed/Hold messages, and, when using the MAS 2 display format, CDAP information.

GA pilots successfully used a CDTI and related SATS HVO procedures, to self-separate from and sequence their ownship aircraft with a single traffic aircraft into a non-towered, non-radar equipped airport during IMC, 100-percent of the time under the conditions of the SSS Flight Experiment. Quantitative analyses of the flight path deviation data (altitude, lateral path, and airspeed as well as adherence to the PTS performance criteria) suggest that a GA pilot's ability to fly an instrument approach is not adversely affected by the additional tasks of self-separating and sequencing using SATS HVO procedures. Furthermore, analyses of qualitative data collected during this experiment indicate that the level of workload experienced by a pilot, while flying an instrument approach and performing self-separation and sequencing tasks using SATS HVO procedures, is no greater than that experienced when performing baseline (i.e., current day) approaches.



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## APPENDIX A. Time-Coded Data Recorded by the Data Acquisition System (DAS)

State variables and lateral flight path deviation were the primary measurement types; however, supporting measurements including rates, accelerations, and control positions were also recorded. All data analyses were performed on parameters sampled at five samples per second.

- |   |  |
|---|--|
| <ul style="list-style-type: none"> <li>• Manifold Pressure (in inches of mercury)</li> <li>• Side Stick (pitch in inches; roll in degrees)</li> <li>• Throttle (in inches)</li> <li>• Rudder Position (in degrees)</li> <li>• Flaps (in degrees)</li> <li>• Global Positioning System (GPS) Time</li> <li>• Latitude (in degrees, minutes, and seconds)</li> <li>• Longitude (in degrees, minutes, and seconds)</li> <li>• Magnetic Heading (in degrees)</li> <li>• True Heading (in degrees)</li> <li>• Pitch Attitude (in degrees)</li> <li>• Roll Attitude (in degrees)</li> <li>• Roll Rate (in degrees per second)</li> <li>• Pitch Rate (in degrees per second)</li> <li>• Yaw Rate (in degrees per second)</li> <li>• Heading Rate (in degrees per second)</li> <li>• Filtered Roll Rate (in degrees per second)</li> <li>• Filtered Pitch Rate (in degrees per second)</li> <li>• Filtered Yaw Rate (in degrees per second)</li> <li>• Filtered Heading Rate (in degrees per second)</li> <li>• Turn Coordinator Rate (in degrees per second)</li> <li>• X Acceleration (in Gs)</li> <li>• Y Acceleration (in Gs)</li> <li>• Z Acceleration (in Gs)</li> <li>• Filtered X Acceleration (in Gs)</li> </ul> | <ul style="list-style-type: none"> <li>• Filtered Y Acceleration (in Gs)</li> <li>• Filtered Z Acceleration (in Gs)</li> <li>• Indicated Airspeed (in knots)</li> <li>• Calibrated Airspeed (in knots)</li> <li>• True Airspeed (in knots)</li> <li>• Filtered Indicated Airspeed (in knots)</li> <li>• Filtered True Airspeed (in knots)</li> <li>• Vertical Speed (in feet per minute)</li> <li>• Filtered Vertical Speed (in feet per minute)</li> <li>• Ground Speed (in knots)</li> <li>• Pressure Altitude (in feet)</li> <li>• Filtered Pressure Altitude (in feet)</li> <li>• True Altitude (in feet)</li> <li>• Filtered True Altitude (in feet)</li> <li>• Outside Air Temperature (in degrees Celsius)</li> <li>• Track Angle (in degrees)</li> <li>• Elevator (in degrees)</li> <li>• Destination Waypoint</li> <li>• Distance to Waypoint</li> <li>• Lateral Path Deviation (in nautical miles)</li> <li>• Track (in degrees)</li> <li>• Desired Track (in degrees)</li> <li>• Groundspeed (in knots)</li> <li>• Bearing to Destination (in degrees)</li> <li>• Discrete signals from each event marker in the cabin</li> </ul> |
|---|--|

## APPENDIX B. Correction Equations Used for the Air Data, Attitude and Heading Reference System (ADAHRS) and Data Acquisition System (DAS)

The Evaluation Pilots (EPs) used standard flight instrumentation to control airspeed, altitude, and vertical speed during the Small Aircraft Transportation System (SATS) Higher Volume Operations (HVO) Self-Separation and Sequencing (SSS) Flight Experiment. This instrumentation included an altimeter, airspeed indicator, and vertical speed indicator, all of which are mechanical, panel-mounted instruments that measure air pressures within the pitot-static system to provide analog outputs. None of these instruments provided digital information that was needed by the research software or for recording in the data acquisition system (DAS). However, this information was available in digital formats from the Air Data, Attitude, and Heading Reference System (ADAHRS) that is part of the baseline research system on the test aircraft.

It was necessary to correct the digital data from the ADAHRS to match similar analog data provided to the EP by the standard flight instrumentation. Data to develop the equations used for these corrections were attained during ground tests by simulating specific pressure changes to the pitot-static system on the aircraft. The aircraft's instruments were "tapped" before each indication was recorded to account for in-flight vibration. Airspeed measurements were taken in increments of 10 knots (kts), from 80 to 130 kts; altitude measurements were taken in increments of 100 feet (ft.), from 1900 to 6100 ft.; and vertical speed measurements were taken in increments of 100 feet per minute (fpm), from -1200 to 500 fpm. All of these data were recorded in both ascending and descending order.

A linear correlation was made between the ADAHRS data and the standard flight instrumentation data to derive the following correction equations for vertical speed, airspeed, and altitude provided by the ADAHRS. These equations were used by the research software on a real-time basis.

Vertical speed	$Y = 1.0442X + 1.4555$	fpm
Airspeed	$Y = 0.8345X + 28.715$	kts.
Altitude	$Y = 0.9951X - 81.249$	ft.

Where:

X is uncorrected data

Y corrected data

## APPENDIX C. Details Regarding Flight Path Parameter Deviation Data Extraction and Reduction

The flight path deviation data that were analyzed to assess the Evaluation Pilot's (EP) ability to fly the global positioning system (GPS) approaches with the Small Aircraft Transportation System (SATS) Higher Volume Operations (HVO) procedures were flight parameters that were to remain constant or nulled during flight. The EPs were instructed to null lateral path deviation and maintain constant airspeed during all segments of the approach path and maintain constant altitude during the level-flight segments.

Each of the test conditions contained flight paths that had multiple level-flight segments followed by descent segments. A methodology was developed to consistently determine when the EP had transitioned between level-flight and descending path segments with enough time for the altitude and vertical speeds to become stable for their appropriate segments. Once the start and stop times for each path segment for each test run was established, the data could be further sectioned for the calculation of root mean squared error (RMSE) values.

The following exponential moving average (EMA) of altitude was applied to establish a consistent method of determining flight segments:

$$(C1) \quad \text{Exponential Moving Average} = (\text{Current Data Value} \times (\text{Exponential Percentage})) + (\text{previous exponential moving average value} \times (1 - (\text{Exponential Percentage})))$$

The relationship of the moving average calculation of the altitude parameter was compared to the value of the parameter itself. In an EMA, more weight is given to more recent data. The greater weight helped determine (within a shorter period) an intent by the EP to either maintain altitude, initiate a descent, or level off. The flight path parameter deviation data were requested at a rate of five samples per second (sps). EMA was calculated over a period of 5 seconds, or 25 samples.

$$(C2) \quad \text{Exponential Percentage} = \frac{2}{\text{Samples} + 1} = \frac{2}{25 + 1} = 0.077$$

Substituting the above value, the EMA formula is as follows:

$$(C3) \quad \text{Exponential Moving Average} = (\text{Current Data Value} \times 0.077) + (\text{previous exponential moving average value}) \times (1 - 0.077)$$

For the first calculation of the EMA, the current data value of altitude was used as input for the "previous EMA value." Subsequently, this first calculation of EMA became the value for the "previous EMA value," and the EMA calculation was performed on all subsequent altitude data. Ideally, when the EMA minus the current altitude is less than zero (i.e.,  $\text{EMA} - \text{current altitude} < 0$ ), this would signal the beginning of a descent. However, "whiplash" was observed where the difference between the EMA and the current altitude data value became negative and shortly thereafter became positive again (i.e.,

representing a false indication). To reduce the false indications, a value of -0.5 was used. When the value of “EMA - current altitude” approached -0.5 from above, false indications were greatly reduced. When the value of “EMA - current altitude” approached the value -0.5 from below, the EP was leveling off from a descent. Using the EMA method of segmenting data, the flight segments for the beginning of descent and the beginning of level off could be consistently determined with minimum subjective judgment required by the experimenters.

To eliminate each EP’s transition from level-flight to a descent and vice versa, only the middle 30 seconds of descent between the start of descent and level off were analyzed. This helped ensure that the data that were analyzed corresponded to the point at which the EP reached, and was attempting to maintain, a constant rate of descent.

For each flight segment, root mean squared error (RMSE) values were determined by using the corrected data and measuring their deviation from a “target value.” Target values were defined from instrument approach procedures and included altitudes, airspeeds, and lateral path deviations. Given the deviation from the targeted value, the RMSE values associated with altitude and airspeed could be calculated for every straight-and-level segment; airspeed RMSE values could be calculated for all descent segments; and lateral path deviation RMSE values could be calculated for all segments except those involving holding patterns. The equation used to calculate RMSE values was as follows:

$$(C4) \quad RMSE = \sqrt{\frac{\sum_{i=1}^N (\text{ParameterActual} - \text{ParameterTarget})^2}{N}}$$

In this equation, “parameter actual” is represented by the corrected raw data, and “N” is the number of data points used in the flight segment RMSE calculation. Target values were depicted by the instrument approach charts provided to the EPs prior to the experiment flight. The target values for each parameter depended upon the flight segment definition such that:

- The airspeed target was 120 knots (kts) prior to the Final Approach Fix (FAF) and was applied to all flight segments; and
- Altitude targets varied from 5,500 feet (ft.) to 2,420 ft. and were applied to only the straight-and-level defined flight segments in each test condition.

Once the RMSE value was calculated for each applicable parameter in each flight segment, a total average value was calculated for each parameter recorded during a given replicate of a given test condition for a given EP. Table C1 shows a sample test condition RMSE table.

Table C1. Root Mean Squared Error (RMSE) Values Collected from an Evaluation Pilot during the First Replicate of the Straight In, In-Trail Approach using the Method of Approach Separation 2 Display Format

Flight Segment	Airspeed (in knots)	Altitude (in feet)	Lateral Path deviation (in nautical miles)
Level 5500	1.01	42.97	0.09
Descent to 4500	4.37	Not Applicable	0.13
Level 4500	3.21	25.48	0.09
Descent to 3700	0.92	Not Applicable	0.17
Level 3700	3.00	15.75	0.16
Average RMSE:	2.50	28.07	0.13

The average RMSE values (Table C1) were analyzed by way of 2 (Approach Type) x 3 (Display Type) x 2 (Replicate) Analysis of Variance (ANOVA) tests.

Adherence to the Federal Aviation Administration's (FAA) Instrument Rating Practical Test Standards (PTS) was determined using the same target values used in calculating the RMSE values for each flight path parameter [C1]. These target values represented the "correct" instrumentation reading that the EP was instructed to "fly to" during the test conditions' different flight segments. The number and duration of each failure to adhere to the PTS associated with each flight path parameter was determined for each flight segment completed by each EP during each replicate of each test condition. Then, for a given flight path parameter, the total time associated with failures to fly within the PTS performance criteria was divided by the total time flying to obtain a percentage of time spent flying out of PTS conformance. These percentage values were analyzed by way of 2 (Approach Type) x 3 (Display Type) x 2 (Replicate) Analysis of Variance (ANOVA) tests.

## Reference

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## **APPENDIX D. Detailed Results of Flight Path Parameter Deviation Data Analyses**

Deviations from assigned altitude, airspeed, and the lateral path deviation from the assigned route on the instrument approach were used to quantify Evaluation Pilots' (EPs) flight performance. Root mean squared error (RMSE) values were calculated for these parameters for each test run. Then, a series of 2 (Approach Type) x 3 (Display Type) x 2 (Replicate) Analysis of Variance (ANOVA) tests was conducted on the RMSE values of altitude, airspeed, and lateral path deviations to determine if significant differences existed in these values when a given display type was used during a given approach type [D1, D2, D3].

The main effects of approach type and display type and the Approach Type x Display Type interaction effect were of primary interest. Means and standard deviations associated with the main effect of replicate and interaction effects involving the replicate factor are not presented unless they were found to be significant. Since the main effect of subjects is usually significant in these types of analyses, it is not specifically mentioned unless it was found to be not significant. For all statistical tests, a 5-percent significance level was set a priori.

### **Altitude Deviation**

The 2 x 3 x 2 ANOVA conducted on the RMSE values of altitude revealed that:

- No significant difference was found to exist between the altitude RMSE values associated with each approach type ( $F [1, 5] = 0.004$ ;  $p = 0.954$ ).
- No significant difference was found to exist among the altitude RMSE values associated with the use of different display types ( $F [2, 10] = 3.30$ ;  $p = 0.079$ ).
- A significant difference was found to exist between the altitude RMSE values associated with each replicate ( $F [1, 5] = 7.44$ ;  $p = 0.041$ ). The occurrence of smaller altitude deviations when EPs completed the second replicate is most likely a result of a practice or learning effect since EPs always performed replicate #2 after completing replicate #1.
- No significant Approach Type x Display Type interaction was found to exist ( $F [2, 10] = 0.56$ ;  $p = 0.591$ ).
- No significant Approach Type x Replicate interaction was found to exist ( $F [1, 5] = 0.17$ ;  $p = 0.698$ ).
- No significant Display Type x Replicate interaction was found to exist ( $F [2, 10] = 0.23$ ;  $p = 0.798$ ).



- No significant Approach Type x Display Type x Replicate interaction was found to exist ( $F [2, 10] = 1.07$ ;  $p = 0.378$ ).

### ***Approach Type***

Table D1 contains the means and standard deviations associated with the altitude deviation data [RMSE values in feet (ft.)] attained for straight-in, in-trail approaches and simultaneous arrival approaches. Sample size equals 36 since altitude deviations were averaged across the three display types.

Table D1. Root Mean Squared Error Altitude Deviations Associated with Approach Type

Approach Type	Mean (ft.)	Standard Deviation (ft.)	Sample Size
Straight In, In-trail	39.40	13.99	36
Simultaneous Arrival	39.52	12.46	36

EPs maintained assigned altitudes equally well when they performed straight-in, in-trail approaches and when they performed simultaneous arrival approaches.

### ***Display Type***

Table D2 contains the means and standard deviations associated with the altitude deviation data (RMSE values in ft.) attained for the Baseline display format, the MAS 1 display format, and the MAS 2 display format. Sample size equals 24 since altitude deviations were averaged across the two approach types.

Table D2. Root Mean Squared Error Altitude Deviations Associated with Display Type

Display Type	Mean (ft.)	Standard Deviation (ft.)	Sample Size
Baseline	37.53	11.76	24
Method of Approach Separation 1	37.88	8.95	24
Method of Approach Separation 2	42.98	10.25	24

EPs maintained assigned altitudes equally well when they performed approaches using the Baseline display format, the MAS 1 display format, and the MAS 2 display format.

### ***Replicate***

Table D3 contains the means and standard deviations associated with the altitude deviation data (RMSE values in ft.) attained for replicate #1 and replicate #2. Sample size equals 36 since altitude

deviations were collected from six EPs, each of whom completed a series of six test conditions twice.

Table D3. Root Mean Squared Error Altitude Deviations Associated with Display Type

Replicate	Mean (ft.)	Standard Deviation (ft.)	Sample Size
#1	43.57	13.32	36
#2	35.35	11.78	36

As noted earlier, the ANOVA revealed that the main effect of replicate was statistically significant. An examination of the mean altitude deviations associated with each replicate shows that smaller altitude deviations occurred when EPs completed the second replicate. This finding is most likely a result of a practice or learning effect since EPs always performed replicate #2 after completing replicate #1.

### ***Approach Type x Display Type***

Table D4 and Figure D1 contain the means and standard deviations associated with the altitude deviation data (RMSE values in ft.) attained when straight-in, in-trail approaches and simultaneous arrival approaches were performed using different display types. Sample size equals 12 since altitude deviations were not averaged across approach type or display type.

Table D4. Root Mean Squared Error Altitude Deviations Associated with Approach Type x Display Type

Test Condition	Mean (ft.)	Standard Deviation (ft.)	Sample Size
Straight In, In-trail Approach / Baseline Display Format	36.82	13.69	12
Simultaneous Arrival Approach / Baseline Display Format	38.24	14.41	12
Straight In, In-trail Approach / Method of Approach Separation 1 Display Format	36.64	11.91	12
Simultaneous Arrival Approach / Method of Approach Separation 1 Display Format	39.11	11.13	12
Straight In, In-trail Approach / Method of Approach Separation 2 Display Format	44.75	15.70	12
Simultaneous Arrival Approach / Method of Approach Separation 2 Display Format	41.20	12.54	12

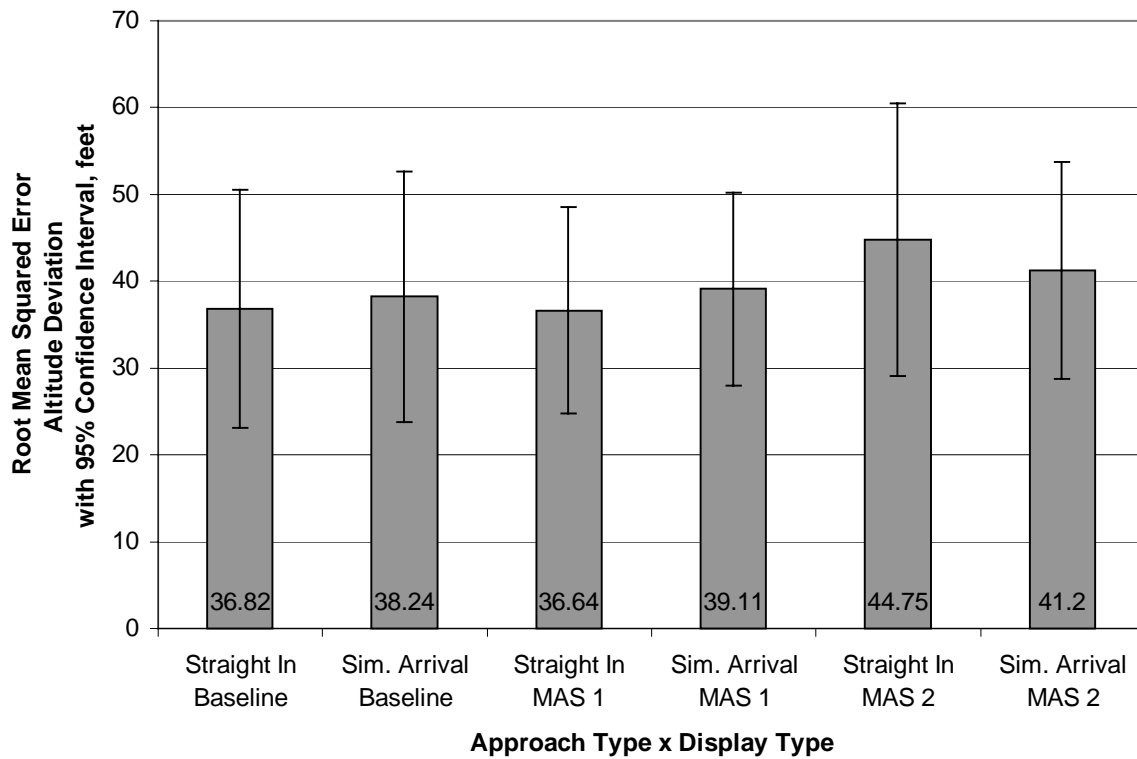


Figure D1. Mean altitude deviations associated with Approach Type x Display Type.

EPs maintained assigned altitudes equally well when they performed different approach types using different types of displays.

### Airspeed Deviation

The 2 x 3 x 2 ANOVA conducted on the RMSE values of airspeed revealed that:

- A significant difference was found to exist between the airspeed RMSE values associated with each approach type ( $F [1, 5] = 6.80$ ;  $p = 0.048$ ).
- No significant difference was found to exist among the airspeed RMSE values associated with the use of different display types ( $F [2, 10] = 0.49$ ;  $p = 0.627$ ).
- No significant difference was found to exist between the airspeed RMSE values associated with each replicate ( $F [1, 5] = 0.90$ ;  $p = 0.386$ ).
- No significant Approach Type x Display Type interaction was found to exist ( $F [2, 10] = 0.55$ ;  $p = 0.595$ ).

- No significant Approach Type x Replicate interaction was found to exist ( $F [1, 5] = 0.01$ ;  $p = 0.939$ ).
- No significant Display Type x Replicate interaction was found to exist ( $F [2, 10] = 0.13$ ;  $p = 0.883$ ).
- No significant Approach Type x Display Type x Replicate interaction was found to exist ( $F [2, 10] = 0.28$ ;  $p = 0.763$ ).

### ***Approach Type***

Table D5 contains the means and standard deviations associated with the airspeed deviation data [RMSE values in knots (kts)] attained for straight-in, in-trail approaches and simultaneous arrival approaches. Sample size equals 36 since airspeed deviations were averaged across the three display types.

Table D5. Root Mean Squared Error Airspeed Deviations Associated with Approach Type

Approach Type	Mean (kts)	Standard Deviation (kts)	Sample Size
Straight In, In-trail	3.11	1.34	36
Simultaneous Arrival	2.85	0.99	36

Since the ANOVA revealed that the main effect of approach type was statistically significant, a simple examination of the mean airspeed deviations associated with each approach type was used to determine if greater airspeed deviations occurred during the straight-in, in-trail approaches or during the simultaneous arrival approaches. When airspeed RMSE values were averaged across the three display types, the mean airspeed deviation was 2.85 kts during the simultaneous arrival approaches, and the mean airspeed deviation was 3.11 kts during the straight-in, in-trail approaches. Statistically, EPs were able to maintain assigned airspeeds more accurately during the simultaneous arrival approaches than during the straight-in, in-trail approaches. However, a mean airspeed difference of just one-quarter of a knot is operationally insignificant.

### ***Display Type***

Table D6 contains the means and standard deviations associated with the airspeed deviation data (RMSE values in kts) attained for the Baseline display format, the MAS 1 display format, and the MAS 2 display format. Sample size equals 24 since airspeed deviations were averaged across the two approach types.

Table D6. Root Mean Squared Error Airspeed Deviations Associated with Display Type

Display Type	Mean (kts)	Standard Deviation (kts)	Sample Size
Baseline	2.92	1.20	24
Method of Approach Separation 1	3.01	1.13	24
Method of Approach Separation 2	3.01	1.24	24

EPs maintained assigned airspeed equally well when they performed approaches using the Baseline display format, the MAS 1 display format, and the MAS 2 display format.

### ***Approach Type x Display Type***

Table D7 and Figure D2 contain the means and standard deviations associated with the airspeed deviation data (RMSE values in kts) attained when straight-in, in-trail approaches and simultaneous arrival approaches were performed using different display types. Sample size equals 12 since airspeed deviations were not averaged across approach type or display type.

Table D7. Airspeed Deviations (Root Mean Squared Error values in knots) Associated with Approach Type x Display Type

Test Condition	Mean (kts)	Standard Deviation (kts)	Sample Size
Straight In, In-trail Approach / Baseline Display Format	2.83	1.09	12
Simultaneous Arrival Approach / Baseline Display Format	3.02	1.35	12
Straight In, In-trail Approach / Method of Approach Separation 1 Display Format	3.28	1.48	12
Simultaneous Arrival Approach / Method of Approach Separation 1 Display Format	2.74	0.57	12
Straight In, In-trail Approach / Method of Approach Separation 2 Display Format	2.81	0.95	12
Simultaneous Arrival Approach / Method of Approach Separation 2 Display Format	3.22	1.48	12

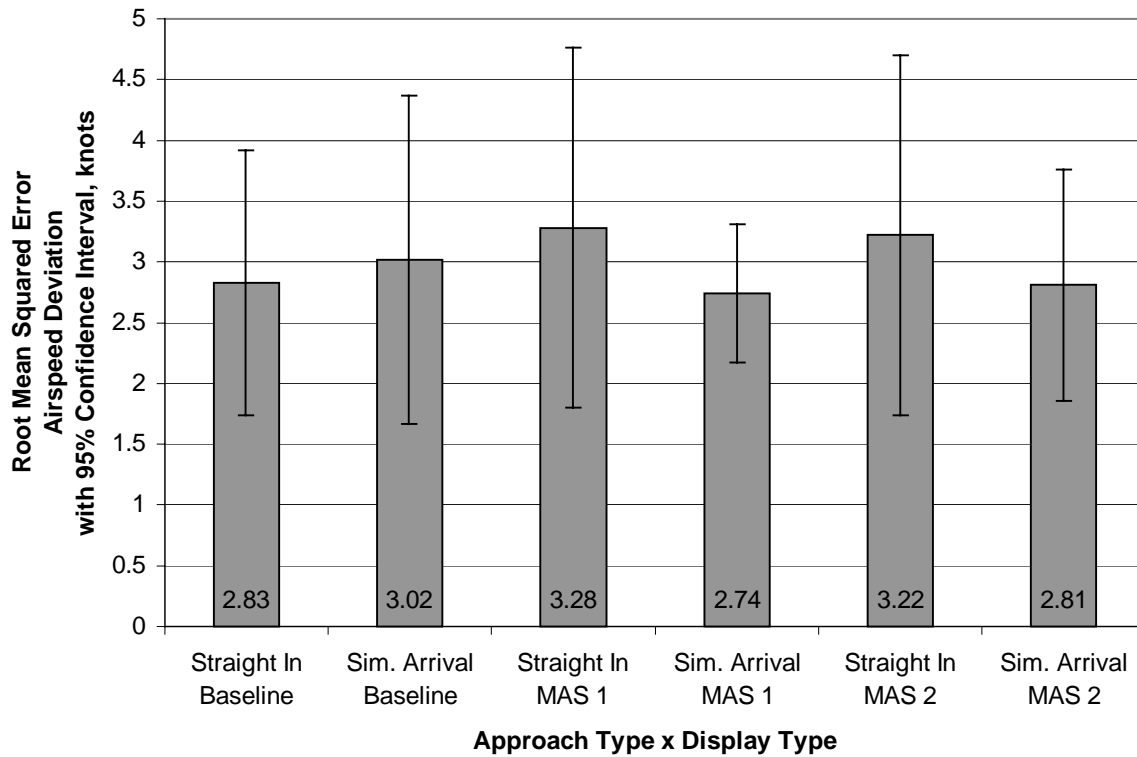


Figure D2. Mean airspeed deviations associated with Approach Type x Display Type.

EPs maintained assigned airspeeds equally well when they performed different approach types using different types of displays.

### Lateral Path Deviation

The 2 x 3 x 2 ANOVA conducted on the RMSE values of lateral path deviation revealed that:

- No significant difference was found to exist between the lateral path deviation RMSE values associated with each approach type ( $F [1, 5] = 0.94$ ;  $p = 0.376$ ).
- No significant difference was found to exist among the lateral path deviation RMSE values associated with the use of different display types ( $F [2, 10] = 1.43$ ;  $p = 0.284$ ).
- No significant difference was found to exist between the lateral path deviation RMSE values associated with each replicate ( $F [1, 5] = 1.49$ ;  $p = 0.276$ ).
- No significant Approach Type x Display Type interaction was found to exist ( $F [2, 10] = 2.08$ ;  $p = 0.176$ ).

- No significant Approach Type x Replicate interaction was found to exist ( $F [1, 5] = 1.08$ ;  $p = 0.345$ ).
- No significant Display Type x Replicate interaction was found to exist ( $F [2, 10] = 0.90$ ;  $p = 0.435$ ).
- No significant Approach Type x Display Type x Replicate interaction was found to exist ( $F [2, 10] = 0.55$ ;  $p = 0.591$ ).

### ***Approach Type***

Table D8 contains the means and standard deviations associated with the lateral path deviation data [RMSE values in nautical miles (n. m.)] attained for straight-in, in-trail approaches and simultaneous arrival approaches. Sample size equals 36 since lateral path deviations were averaged across the three display types.

Table D8. Root Mean Squared Error Lateral Path Deviations Associated with Approach Type

Approach Type	Mean (n. m.)	Standard Deviation (n. m.)	Sample Size
Straight In, In-trail	0.08	0.04	36
Simultaneous Arrival	0.07	0.05	36

EPs maintained the assigned course equally well when they performed straight-in, in-trail approaches and when they performed simultaneous arrival approaches.

### ***Display Type***

Table D9 contains the means and standard deviations associated with the lateral path deviation data (RMSE values in n. m.) attained for the Baseline display format, the MAS 1 display format, and the MAS 2 display format. Sample size equals 24 since lateral path deviations were averaged across the two approach types.

Table D9. Root Mean Squared Error Lateral Path Deviations Associated with Display Type

Display Type	Mean (n. m.)	Standard Deviation (n. m.)	Sample Size
Baseline	0.07	0.05	24
Method of Approach Separation 1	0.09	0.05	24
Method of Approach Separation 2	0.07	0.03	24

EPs maintained assigned course equally well when they performed approaches using the Baseline display format, the MAS 1 display format, and the MAS 2 display format.

### *Approach Type x Display Type*

Table D10 and Figure D3 contain the means and standard deviations associated with the lateral path deviation data (RMSE values in n. m.) attained when straight-in, in-trail approaches and simultaneous arrival approaches were performed using different display types. Sample size equals 12 since lateral path deviations were not averaged across approach type or display type.

Table D10. Root Mean Squared Error Lateral Path Deviations Associated with Approach Type x Display Type

Test Condition	Mean (n. m.)	Standard Deviation (n. m.)	Sample Size
Straight In, In-trail Approach / Baseline Display Format	0.07	0.03	12
Simultaneous Arrival Approach / Baseline Display Format	0.08	0.06	12
Straight In, In-trail Approach / Method of Approach Separation 1 Display Format	0.10	0.05	12
Simultaneous Arrival Approach / Method of Approach Separation 1 Display Format	0.07	0.05	12
Straight In, In-trail Approach / Method of Approach Separation 2 Display Format	0.07	0.03	12
Simultaneous Arrival Approach / Method of Approach Separation 2 Display Format	0.07	0.03	12



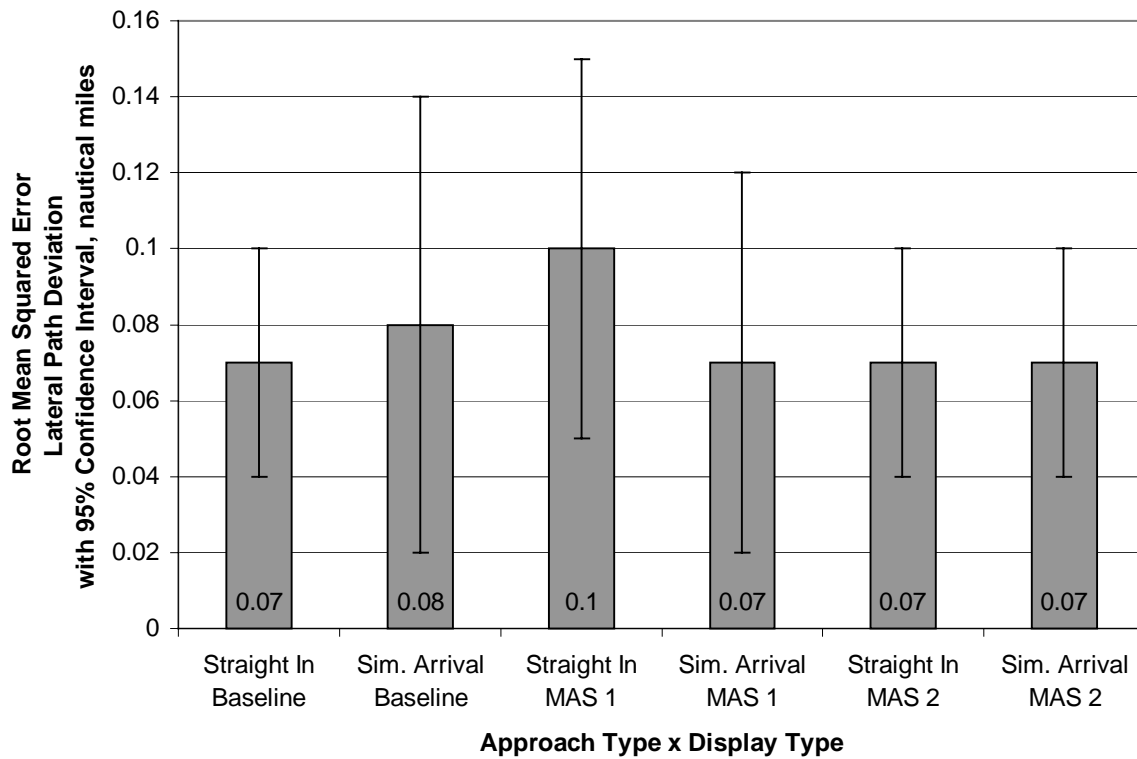


Figure D3. Mean lateral path deviations associated with Approach Type x Display Type.

EPs maintained assigned course equally well when they performed different approach types using different types of displays.

## References

- [D1] Keppel, G.: *Design and Analysis: A Researcher's Handbook*. Third ed., Prentice-Hall, Inc., 1991.
- [D2] Norusis, M. J.: *SPSS® for Windows™: Base System User's Guide, Release 6.0*. SPSS Inc. (Chicago, IL), 1993.
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## **APPENDIX E. Detailed Results of Adherence to PTS for the Instrument Rating Data Analyses**

Percentages of time that Evaluation Pilots (EPs) failed to adhere to the Practical Test Standards (PTS) for the Instrument Rating were used to quantify flight performance. The duration (i.e., elapsed time in seconds) of each failure to fly within the PTS was the difference between the point in time when a PTS parameter was breached and the point in time when adherence to that PTS parameter was regained. For a given flight path parameter, the total time associated with failures to fly within PTS performance criteria was divided by the total time flying to obtain a percentage of time spent flying out of PTS conformance.

Percentages of time that EPs failed to adhere to the PTS were calculated for altitude, airspeed, and lateral path deviation. Data used to assess PTS conformance were obtained from 30-second segments during descents where the parameters would be stabilized. Airspeed and lateral path deviation data were assessed during both level-flight and descents. Altitude data were assessed only during level-flight segments. All EPs successfully adhered to the PTS performance criteria for lateral tracking for the Instrument Rating (i.e.,  $\pm 1.0$  n. m. prior to the FAF, and  $\pm 0.225$  n. m. after the FAF) 100-percent of the time. Therefore, 2 (Approach Type) x 3 (Display Type) x 2 (Replicate) ANOVAs were conducted on the percentages of time that EPs failed to adhere to the PTS for altitude and airspeed to determine if significant differences existed in these values when a given display type was used during a given approach type [E1, E2, E3].

The main effects of approach type and display type and the Approach Type x Display Type interaction effect were of primary interest. Means and standard deviations associated with the main effect of replicate and interaction effects involving the replicate factor are not presented unless they were found to be significant. Since the main effect of subjects is usually significant in these types of analyses, it is not specifically mentioned unless it was found to be not significant. For all statistical tests, a 5-percent significance level was set a priori.

### **Adherence to Altitude PTS**

The 2 x 3 x 2 ANOVA conducted on the percentages of time that EPs failed to adhere to the PTS for altitude revealed that:

- No significant difference was found to exist among the percentages of altitude PTS nonconformance associated with subjects ( $F [1, 5] = 6.18$ ;  $p = 0.055$ ).
- No significant difference was found to exist between the percentages of altitude PTS nonconformance associated with each approach type ( $F [1, 5] = 3.46$ ;  $p = 0.122$ ).
- No significant difference was found to exist among the percentages of altitude PTS nonconformance associated with the use of different display types ( $F [2, 10] = 0.09$ ;  $p = 0.918$ ).

- No significant difference was found to exist between the percentages of altitude PTS nonconformance associated with each replicate ( $F [1, 5] = 2.44$ ;  $p = 0.179$ ).
- No significant Approach Type x Display Type interaction was found to exist ( $F [2, 10] = 1.29$ ;  $p = 0.317$ ).
- No significant Approach Type x Replicate interaction was found to exist ( $F [1, 5] = 0.18$ ;  $p = 0.687$ ).
- No significant Display Type x Replicate interaction was found to exist ( $F [2, 10] = 0.55$ ;  $p = 0.592$ ).
- No significant Approach Type x Display Type x Replicate interaction was found to exist ( $F [2, 10] = 1.17$ ;  $p = 0.350$ ).

### ***Subjects***

Across EPs, there was very little variability among the percentages of altitude PTS nonconformance. EPs adhered to the altitude PTS in a very consistent manner with each other across the test conditions.

### ***Approach Type***

Table E1 contains the means and standard deviations associated with the percentages of altitude PTS nonconformance attained for straight-in, in-trail approaches and simultaneous arrival approaches. Sample size equals 36 since percentages were averaged across the three display types.

Table E1. Percentages of Altitude PTS Nonconformance Associated with Approach Type

Approach Type	Mean	Standard Deviation	Sample Size
Straight In, In-trail	1.08	2.71	36
Simultaneous Arrival	2.01	3.23	36

EPs adhered to the altitude PTS equally well when they performed straight-in, in-trail approaches and when they performed simultaneous arrival approaches.

### ***Display Type***

Table E2 contains the means and standard deviations associated with the percentages of altitude PTS nonconformance attained for the Baseline display format, the MAS 1 display format, and the MAS 2 display format. Sample size equals 24 since percentages were averaged across the two approach types.

Table E2. Percentages of Altitude PTS Nonconformance Associated with Display Type

Display Type	Mean	Standard Deviation	Sample Size
Baseline	1.52	3.48	24
Method of Approach Separation 1	1.68	2.28	24
Method of Approach Separation 2	1.43	3.23	24

EPs adhered to the altitude PTS equally well when they performed approaches using the Baseline display format, the MAS 1 display format, and the MAS 2 display format.

### *Approach Type x Display Type*

Table E3 and Figure E1 contain the means and standard deviations associated with the percentages of altitude PTS nonconformance attained when straight-in, in-trail approaches and simultaneous arrival approaches were performed using different display types. Sample size equals 12 since percentages were not averaged across approach type or display type.

Table E3. Percentages of Altitude PTS Nonconformance Associated with Approach Type x Display Type

Test Condition	Mean	Standard Deviation	Sample Size
Straight In, In-trail Approach / Baseline Display Format	0.75	1.86	12
Simultaneous Arrival Approach / Baseline Display Format	2.30	4.53	12
Straight In, In-trail Approach / Method of Approach Separation 1 Display Format	0.71	1.47	12
Simultaneous Arrival Approach / Method of Approach Separation 1 Display Format	2.65	2.57	12
Straight In, In-trail Approach / Method of Approach Separation 2 Display Format	1.77	4.11	12
Simultaneous Arrival Approach / Method of Approach Separation 2 Display Format	1.09	2.16	12

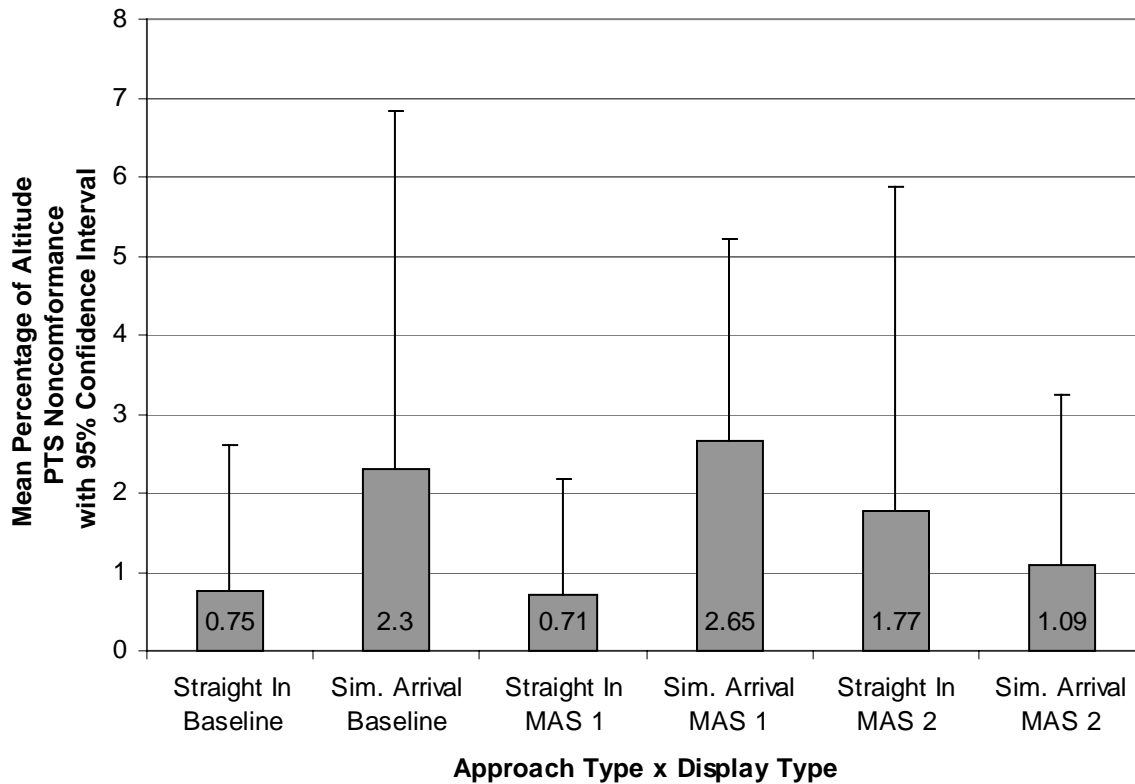


Figure E1. Mean percentages of altitude Practical Test Standard (PTS) nonconformance associated with Approach Type x Display Type.

EPs adhered to the altitude PTS equally well when they performed different approach types using different types of displays.

### Adherence to Airspeed PTS

The 2 x 3 x 2 ANOVA conducted on the percentages of time that EPs failed to adhere to the PTS for airspeed revealed that:

- No significant difference was found to exist among the percentages of airspeed PTS nonconformance associated with subjects ( $F [1, 5] = 2.38$ ;  $p = 0.183$ ).
- No significant difference was found to exist between the percentages of airspeed PTS nonconformance associated with each approach type ( $F [1, 5] = 2.35$ ;  $p = 0.186$ ).
- No significant difference was found to exist among the percentages of airspeed PTS nonconformance associated with the use of different display types ( $F [2, 10] = 2.38$ ;  $p = 0.142$ ).

- No significant difference was found to exist between the percentages of airspeed PTS nonconformance associated with each replicate ( $F [1, 5] = 0.35$ ;  $p = 0.580$ ).
- No significant Approach Type x Display Type interaction was found to exist ( $F [2, 10] = 1.72$ ;  $p = 0.228$ ).
- No significant Approach Type x Replicate interaction was found to exist ( $F [1, 5] = 0.001$ ;  $p = 0.980$ ).
- No significant Display Type x Replicate interaction was found to exist ( $F [2, 10] = 0.17$ ;  $p = 0.849$ ).
- No significant Approach Type x Display Type x Replicate interaction was found to exist ( $F [2, 10] = 0.15$ ;  $p = 0.861$ ).

### ***Subjects***

Across EPs, there was very little variability among the percentages of airspeed PTS nonconformance. EPs adhered to the airspeed PTS in a very consistent manner with each other across the test conditions.

### ***Approach Type***

Table E4 contains the means and standard deviations associated with the percentages of airspeed PTS nonconformance attained for straight-in, in-trail approaches and simultaneous arrival approaches. Sample size equals 36 since percentages were averaged across the three display types.

Table E4. Percentages of Airspeed PTS Nonconformance Associated with Approach Type

Approach Type	Mean	Standard Deviation	Sample Size
Straight In, In-trail	1.11	3.72	36
Simultaneous Arrival	0.30	1.37	36

EPs adhered to the airspeed PTS equally well when they performed straight-in, in-trail approaches and when they performed simultaneous arrival approaches.

### ***Display Type***

Table E5 contains the means and standard deviations associated with the percentages of airspeed PTS

nonconformance attained for the Baseline display format, the MAS 1 display format, and the MAS 2 display format. Sample size equals 24 since percentages were averaged across the two approach types.

Table E5. Percentages of Airspeed PTS Nonconformance Associated with Display Type

Display Type	Mean	Standard Deviation	Sample Size
Baseline	0.48	1.66	24
Method of Approach Separation 1	0.25	0.90	24
Method of Approach Separation 2	1.37	4.49	24

EPs adhered to the airspeed PTS equally well when they performed approaches using the Baseline display format, the MAS 1 display format, and the MAS 2 display format.

### ***Approach Type x Display Type***

Table E6 and Figure E2 contain the means and standard deviations associated with the percentages of airspeed PTS nonconformance attained when straight-in, in-trail approaches and simultaneous arrival approaches were performed using different display types. Sample size equals 12 since percentages were not averaged across approach type or display type.

Table E6. Percentages of Airspeed PTS Nonconformance Associated with Approach Type x Display Type

Test Condition	Mean	Standard Deviation	Sample Size
Straight In, In-trail Approach / Baseline Display Format	0.25	0.62	12
Simultaneous Arrival Approach / Baseline Display Format	0.72	2.30	12
Straight In, In-trail Approach / Method of Approach Separation 1 Display Format	0.50	1.24	12
Simultaneous Arrival Approach / Method of Approach Separation 1 Display Format	0.00*	0.00*	12
Straight In, In-trail Approach / Method of Approach Separation 2 Display Format	2.58	6.22	12
Simultaneous Arrival Approach / Method of Approach Separation 2 Display Format	0.17	0.58	12

\* NOTE: A value of zero indicates conformance 100-percent of the time.

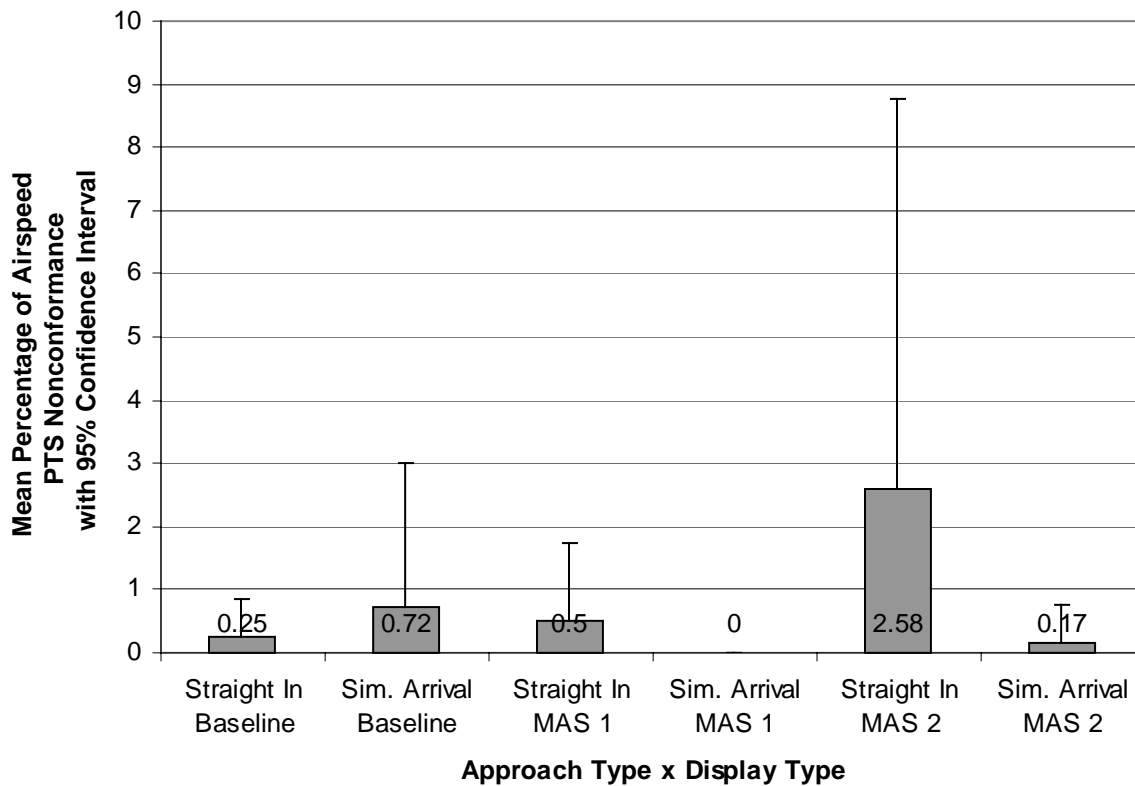


Figure E2. Mean percentages of airspeed Practical Test Standards (PTS) nonconformance associated with Approach Type x Display Type.

EPs adhered to the airspeed PTS equally well when they performed different approach types using different types of displays.

### Adherence to the PTS Performance Criteria for Lateral Tracking

All EPs successfully adhered to the CDI PTS for the Instrument Rating 100-percent of the time during all six of the experiment's test conditions. It was concluded that EPs were able to maintain their course with an appropriate level of precision while performing straight-in, in-trail approaches and simultaneous arrival approaches using the Baseline display format, the MAS 1 display format, and the MAS 2 display format.

### References

- [E1] Keppel, G.: *Design and Analysis: A Researcher's Handbook*. Third ed., Prentice-Hall, Inc., 1991.
- [E2] Norusis, M. J.: *SPSS® for Windows™: Base System User's Guide, Release 6.0*. SPSS Inc. (Chicago, IL), 1993.



[E3] Winer, B. J.; Brown, D. R.; and Michels, K. M.: *Statistical Principles in Experimental Design*. Third ed., McGraw-Hill, Inc., 1991.

## APPENDIX F. Detailed Results of Subjective Workload Data Analyses

Evaluation Pilots (EPs) used the Air Force Flight Test Center's (AFFTC) Seven-Point Subjective Workload Estimate Scale and the Modified Cooper-Harper (MCH) Rating Scale to rate the level of workload that they experienced during each of the experiment's six test conditions [G1, G2]. Since each test condition was performed twice during the course of the experiment, each EP provided 12 AFFTC workload ratings and 12 MCH workload ratings. For each EP, the two AFFTC workload ratings associated with a given test condition were averaged together to yield a set of six mean workload ratings, and the two MCH workload ratings associated with a given test condition were averaged together to yield a set of six mean workload ratings. Nonparametric tests were employed as a conservative method for analyzing workload ratings associated with discrete rating scale items. For all statistical tests, a 5-percent significance level was set a priori.

### Approach Type

#### *AFFTC Workload Ratings*

Table F1 contains the means and standard deviations for the AFFTC workload ratings associated with performing straight-in, in-trail approaches and simultaneous arrival approaches. Sample size equals 18 since workload ratings were averaged across the two replicates and the three display types.

Table F1. Air Force Flight Test Center Workload Estimate Scale Ratings Associated with Approach Type

Approach Type	Mean	Standard Deviation	Sample Size
Straight In, In-trail	2.72	0.52	18
Simultaneous Arrival	2.61	0.53	18

A Wilcoxon Test (i.e., a nonparametric within-subject test appropriate for analyzing two related samples of ordinal data) performed on these means revealed that EPs reported experiencing equivalent levels of workload during the straight-in, in-trail approaches and the simultaneous arrival approaches ( $p = 0.6546$ ) [G3].

#### *MCH Workload Ratings*

Table F2 contains the means and standard deviations of with the MCH workload ratings associated with performing straight-in, in-trail approaches and simultaneous arrival approaches. Sample size equals 18 since workload ratings were averaged across the two replicates and the three display types.

Table F2. Modified Cooper-Harper Workload Ratings Associated with Approach Type

Approach Type	Mean	Standard Deviation	Sample Size
Straight In, In-trail	2.42	0.97	18
Simultaneous Arrival	2.14	1.03	18

A Wilcoxon Test revealed that EPs reported experiencing equivalent levels of workload during the straight-in, in-trail approaches and the simultaneous arrival approaches ( $p = 0.0833$ ).

## Display Type

### *AFFTC Workload Ratings*

Table F3 contains the means and standard deviations for the AFFTC workload ratings associated with performing approaches using the Baseline display format, the MAS 1 display format, and the MAS 2 display format. Sample size equals 12 since workload ratings were averaged across the two replicates and the two approach types.

Table F3. Air Force Flight Test Center Workload Estimate Scale Ratings Associated with Display Type

Display Type	Mean	Standard Deviation	Sample Size
Baseline	2.63	0.53	12
Method of Approach Separation 1	2.63	0.57	12
Method of Approach Separation 2	2.75	0.50	12

A Friedman Test (i.e., a nonparametric within-subject test appropriate for analyzing three or more related samples of ordinal data) performed on these means revealed that EPs reported experiencing equivalent AFFTC workload ratings when different display types were used ( $X^2 [2] = 2.2353$ ;  $p = 0.3270$ ) [G3, G4].

### *MCH Workload Ratings*

Table F4 contains the means and standard deviations for the MCH workload ratings associated with performing approaches using the Baseline display format, the MAS 1 display format, and the MAS 2 display format. Sample size equals 12 since workload ratings were averaged across the two replicates and the two approach types.

Table F4. Modified Cooper-Harper Workload Ratings Associated with Display Type

Display Type	Mean	Standard Deviation	Sample Size
Baseline	2.13	0.98	12
Method of Approach Separation 1	2.38	1.11	12
Method of Approach Separation 2	2.33	0.96	12

A Friedman Test performed on these means revealed that EPs reported experiencing equivalent MCH workload ratings when different display types were used ( $X^2 [2] = 0.7778$ ;  $p = 0.6778$ ).

### Approach Type x Display Type

#### *AFFTC Workload Ratings*

Table F5 and Figure F1 contain the means and standard deviations for the AFFTC workload ratings associated with performing straight-in, in-trail approaches and simultaneous arrival approaches using different display types. Sample size equals 6 since workload ratings were averaged across replicates.

Table F5. Air Force Flight Test Center Workload Estimate Scale Ratings Associated with Approach Type x Display Type

Test Condition	Mean	Standard Deviation	Sample Size
Straight In, In-trail Approach / Baseline Display Format	2.58	0.58	6
Simultaneous Arrival Approach / Baseline Display Format	2.67	0.52	6
Straight In, In-trail Approach / Method of Approach Separation 1 Display Format	2.75	0.52	6
Simultaneous Arrival Approach / Method of Approach Separation 1 Display Format	2.50	0.63	6
Straight In, In-trail Approach / Method of Approach Separation 2 Display Format	2.83	0.52	6
Simultaneous Arrival Approach / Method of Approach Separation 2 Display Format	2.67	0.52	6

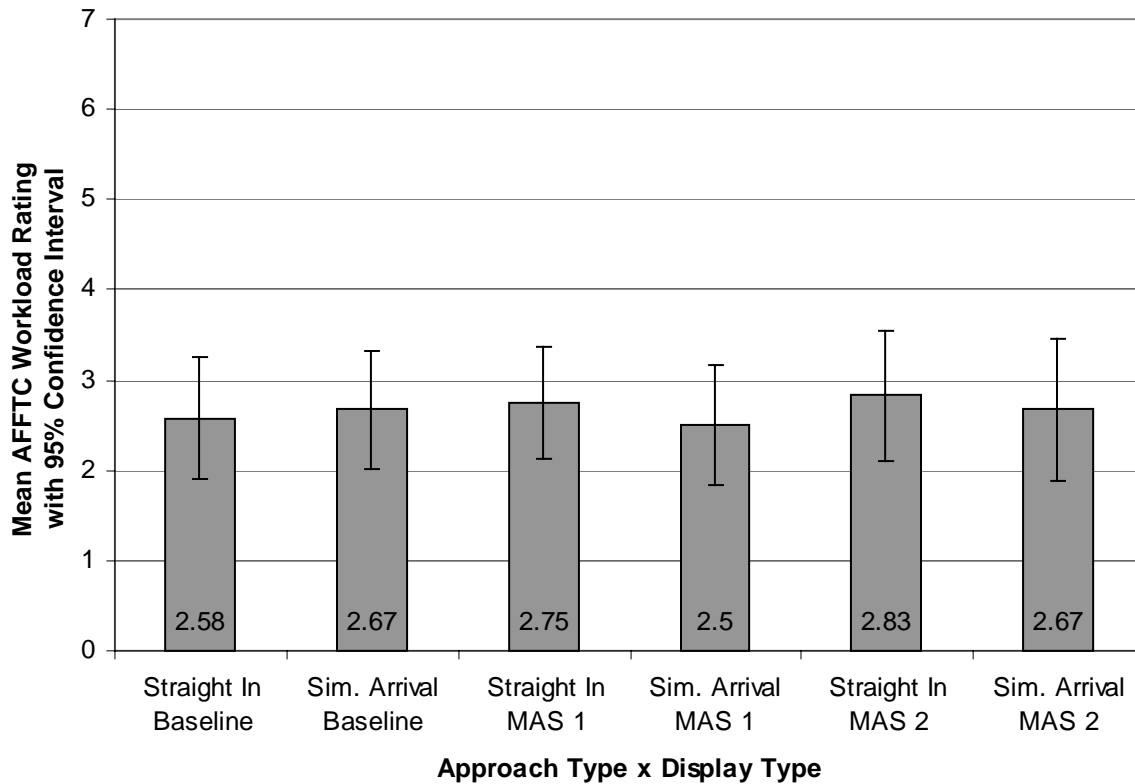


Figure F1. Mean Air Force Flight Test Center (AFFTC) Subjective Workload Estimate Scale ratings associated with Approach Type x Display Type.

A Friedman Test performed on these means revealed that equivalent workload ratings were reported to be experienced when different display types were used during the straight-in, in-trail approaches and the simultaneous arrival approaches ( $X^2 [5] = 2.2519$ ;  $p = 0.8133$ ).

### ***MCH Workload Ratings***

Table F6 and Figure F2 contain the means and standard deviations for the MCH workload ratings associated with performing straight-in, in-trail approaches and simultaneous arrival approaches using different display types. Sample size equals 6 since workload ratings were averaged across replicates.

Table F6. Modified Cooper-Harper Workload Ratings Associated with Approach Type x Display Type

Test Condition	Mean	Standard Deviation	Sample Size
Straight In, In-trail Approach / Baseline Display Format	2.08	1.07	6
Simultaneous Arrival Approach / Baseline Display Format	2.17	0.98	6
Straight In, In-trail Approach / Method of Approach Separation 1 Display Format	2.58	0.97	6
Simultaneous Arrival Approach / Method of Approach Separation 1 Display Format	2.17	1.29	6
Straight In, In-trail Approach / Method of Approach Separation 2 Display Format	2.58	0.97	6
Simultaneous Arrival Approach / Method of Approach Separation 2 Display Format	2.08	0.97	6

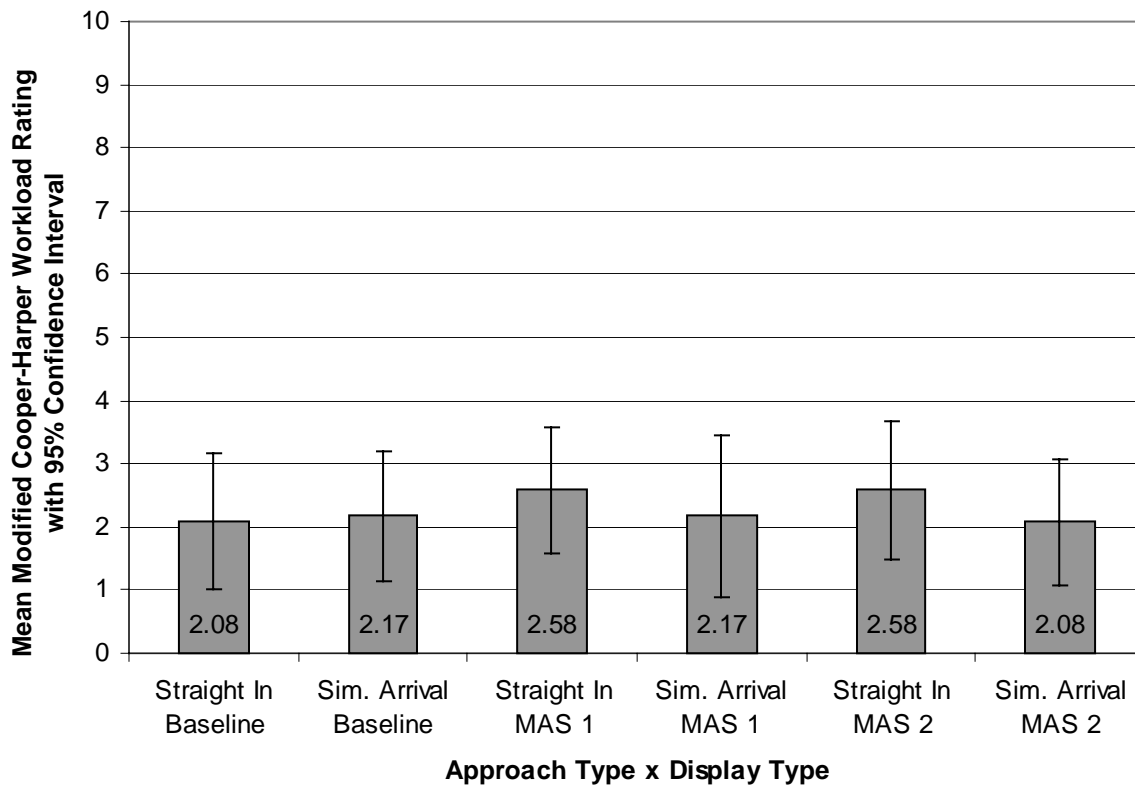


Figure F2. Mean Modified Cooper-Harper (MCH) workload ratings associated with Approach Type x Display Type.

A Friedman Test performed on these means revealed that equivalent workload ratings were reported to be experienced when different display types were used during the straight-in, in-trail approaches and the simultaneous arrival approaches ( $X^2 [5] = 5.0000$ ;  $p = 0.4159$ ).

## References

- [F1] Ames, L. L.; and George, E. J.: *Revision and Verification of a Seven-Point Workload Estimate Scale* (AFFTC-TIM093-01). Air Force Flight Test Center (Edwards Air Force Base, CA), 1993.
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14. ABSTRACT A new flight operations concept called Small Aircraft Transportation System (SATS) Higher Volume Operations (HVO) was developed to increase capacity during Instrument Meteorological Conditions (IMC) at non-towered, non-radar airports by enabling concurrent operations of multiple aircraft. One aspect of this concept involves having pilots safely self-separate from other aircraft during approaches into these airports using appropriate SATS HVO procedures. A flight experiment was conducted to determine if instrument-rated general aviation (GA) pilots could self-separate and sequence their ownship aircraft, while following a simulated aircraft, into a non-towered, non-radar airport during simulated IMC. Six GA pilots' workload levels and abilities to perform self-separation and sequencing procedures while flying a global positioning system (GPS) instrument approach procedure were examined. The results showed that the evaluation pilots maintained at least the minimum specified separation between their ownship aircraft and simulated traffic and maintained their assigned landing sequence 100-percent of the time. Neither flight path deviations nor subjective workload assessments were negatively impacted by the additional tasks of self-separating and sequencing during these instrument approaches.						
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